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Scope and topics

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Analysis of the impact of COVID-19 on the coupling of the material flow and capital flow in a closed-loop supply chain

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A B S T R A C T

The complex and changeable external social and economic environment has a significant impact on the sustainable development of the closed-loop supply chain. In particular, the occurrence of uncertain emergencies increases the risk of interruption of the closed-loop supply chain, making it insufficient to analyze its complex changes from the perspective of material flow alone. Based on this analysis, the paper constructs a closed-loop supply chain material flow and capital flow coupling system composed of manufacturers, sellers and recyclers to explore the impact of material flow sudden interruption on the closed-loop supply chain system when an uncertain emergency occurs. In this paper, based on the closed-loop supply chain system coupled with logistics and capital flow, a system dynamics simulation model was established by using Vensim simulation software to analyze the impact of COVID-19 epidemic on manufacturers, sellers and recyclers under five scenarios. The results show that when COVID-19 outbreaks occur, the material flow of each main enterprise in the closed-loop supply chain is more easily influenced than the capital flow. At the same time, it can be found that the recyclers in the main enterprises of the closed-loop supply chain are more easily influenced by the material flow. The model constructed in this paper has applicability and can be used for related studies of closed-loop supply chain under other emergencies, but the scene design should be carried out according to the characteristics of emergencies themselves.

A R T I C L E I N F O

Keywords:
COVID-19 epidemic;
Supply chain;
Closed-loop supply chain;
Material flow;
Capital flow;
Material-capital flows coupling;
System dynamics;
Simulation;
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1. Introduction

With the rapid development of social economy, many products fail to meet the increasing demands of consumers which to a large extent, accelerate the replacement of products and produces a large number of waste products [1]. The emergence of a large number of these waste products has brought great pressure on social and environmental benefits and economic benefits, which has become the focus of people's attention. People start to turn their attention to *Circular economy* and *Sustainable Development* [2]. Therefore, manufacturers and sellers in the supply chain system and recyclers outside the system start to form a closed-loop supply chain system jointly, and the closed-loop supply chain is such a unity of the forward supply chain and reverse supply chain [3]. The emergence of the closed-loop supply chain makes the subject enterprise's material flow, information flow and capital stream flow inside the closed circulation system, to strengthen the main body of the relationship between the enterprise and the cooperation. It not only makes the enterprise to reduce logistics cost, to enhance logistics efficiency and economic benefit of ascension into a reality, but also improves the environmental benefits and economic benefits of society as a whole, and it has become the focus of the current enterprise [4, 5]. However, some uncertain emergencies may pose great challenges to the stability of the closed-loop supply chain system. Most enterprises shut down and stop production, and the closed-loop supply chain appears to run poorly or even interrupt, which is undoubtedly a major challenge to enterprises and the supply chain itself in the closed-loop supply chain [6, 7].

Based on the background of the COVID-19 outbreak, this paper constructed a dynamics model for closed-loop supply chain system, and studied the impact of the COVID-19 outbreak on each main enterprise of the closed-loop supply chain from the perspective of the coupling of material flow and capital flow. In this paper, a total of 5 scenarios are set up, and the system dynamics model constructed is simulated by using Vensim software, so as to observe the changes of inventory and capital of each main enterprise in the closed-loop supply chain. In addition, suggestions are advanced according to the simulation results to promote the normal operation of the closed-loop supply chain system. This study consists of three main contributions: Firstly, system dynamics enabled us to analyze the changes of each main enterprise in the closed-loop supply chain in a visual way. Secondly, this study abandoned the previous analysis of closed-loop supply chain only from the perspective of material flow, and introduced capital flow to realize the coupling of material flow and capital flow. Thirdly, the analysis results of this paper provided evidence for maintaining the normal operation of the main enterprises and systems of the closed-loop supply chain.

The rest of this paper is organized as follows. Section 2 is a literature review. Section 3 introduces the constructed closed-loop supply chain coupling system. Section 4 studies the affected situation of each main enterprise of the closed-loop supply chain by simulating the dynamic model of the closed-loop supply chain system under five scenarios. Section 5 is related discussion, and Section 6 summarizes main conclusions.

2. Literature review

At present, many scholars have conducted numerous studies on the impact of uncertain emergencies on the closed-loop supply chain. In this section, we introduce some high-quality literature related to the topic of this paper on some aspects of impact, content and research methods.

Through literature analysis, we know that various uncertain factors or events will have a significant impact on the closed-loop supply chain. Morakabatchiankar *et al.* [8] and Cao *et al.* [9] analyzed the impact of uncertain demand on the closed-loop supply chain, and improved the overall environmental and economic benefits of the closed-loop supply chain by integrating product management or supporting retailers. Liao *et al.* [10] concluded that by running optimal remanufacturing theories and policies to guide the remanufacturing activities of scrapped construction machinery products in the context of uncertain procurement and demand, the goal of resource utilization and profit maximization in the closed-loop supply chain can be achieved. Almaraj *et al.* [11] designed a multi-cycle, multi-echelon closed-loop supply chain method to deal with the impact of production quality uncertainty on the closed-loop supply chain. Vandani *et al.* [12] also designed a closed-loop supply chain network with integrated decision-making to alleviate the negative impact of uncertain delivery time on the closed-loop supply chain. Chen *et al.* [13] argued that increasing government subsidies could reduce the incidence of income uncertainty on the closed-loop supply chain. Jessica *et al.* [14] found that the disruption at the downstream level has a greater influence on the production capacity, inventory status, orders and other performance of the supply chain than the disruption at the upstream level by planning multilevel supply chain disruptions. Chen *et al.* [15] built a closed-loop supply chain network physical system that can obtain information such as production, inventory and demand, etc. They believed that when the system was interrupted by interference in the interaction process, the elasticity measurement of supply chain was of great significance for reducing order loss in the supply chain. Cuauhtemoc *et al.* [16] studied the impact of production process interruption caused by mechanical failure on order transportation and company inventory level by taking order transportation as the key performance index. Shao *et al*. [17] took lithium supply chain as an example to analyze the impact of demand shock of new energy vehicles and supply disruption of lithium resources on lithium raw material inventory, lithium product inventory and lithium social use inventory in lithium supply chain. Taking agricultural supply chain as an example, Wang *et al*. [18] studied the dynamic impact of COVID-19 on China's live pigs market price, consumption and pork inventory, and designed five supply chain disruption scenarios.

From the above, we know that the occurrence of various uncertain factors and uncertain events will have an impact on the closed-loop supply chain, and these impacts are often negative. As a large network system, the closed-loop supply chain is influenced and connected by various enterprises and elements within the system. The occurrence of negative influences is bound to affect the robustness of the closed-loop supply chain system. Therefore, in order to improve the ability of the closed-loop supply chain system to cope with external uncertainties and maintain the overall robustness of the closed-loop supply chain system, the research on the robustness of the closed-loop supply chain system cannot be ignored.

Kim *et al*. [19] believed that the uncertainty of reverse logistics would affect the stability of the closed-loop supply chain, and proposed a hybrid holistic model and robust corresponding model to improve the response ability and stability of the closed-loop supply chain system. Hassanpour *et al*. [20] designed a robust closed-loop supply chain network model, and verified its effectiveness in the robustness of closed-loop supply chain through evaluation. Taking lead acid supply chain as an example, Fazli *et al*. [21] proposed an effective robust programming model. Polo *et al*. [22] established a robust programming model of the closed-loop supply chain with finance as the measurement index, and reflected the robustness of the closed-loop supply chain through performance. Abdolazimi *et al*. [23] studied the robust design of the three-stage closed-loop supply chain network under multiple objectives by taking the tire factory as an example. Gholizadeh *et al*. [24] proposed a robust feasible optimization method for the closed-loop supply chain network of disposable electrical appliances to maximize the value of waste electrical appliances. Mohammed *et al*. [25] and Nayeri *et al*. [26] designed a robust model of closed-loop supply chain in the context of uncertainty in the external business environment. Through sensitivity analysis of parameters in the model, the robustness of the model was verified, and the influence of increased uncertainty level at the robustness of closed-loop supply chain was obtained.

In the study of the robustness of closed-loop supply chain, most scholars focused on robustness. They designed a robust programming model of closed-loop supply chain, or propose some robust optimization methods to deal with the impact of uncertainties or emergencies on closed-loop supply chain, so as to maintain the robustness of closed-loop supply chain system.

At the same time, according to literature reading, there are also various methods to study the closed-loop supply chain system based on uncertainty.

Game theory has been used by many scholars as a way to study the interrelationships between system structures. Tan *et al*. [27] used a fuzzy bargaining game to solve the order allocation problem of each main enterprise in the closed-loop supply chain system when the economic market is uncertain, which not only improves the operation efficiency of the system, but also ensures the provision of high-quality service for customer service. Hosseini *et al*. [28] took a pharmaceutical company as an example, proposed a coordination model based on the game theory method, and proved that the coordination model could improve the system's adaptability to damage. Based on the uncertainty of product quality, Minyue *et al*. [29] constructed a game theory model, believing that it is harmful to force manufacturers to adopt warranty premium policies. Wakhid *et al*. [30] established the Stacklberg game model and proves that centralized decision-making under uncertain economic environment can benefit the whole closed-loop supply chain system.

In addition to game theory, some linear or nonlinear programming methods have become common methods for scholars to study closed-loop supply chain systems. Hao *et al*. [31] proposed a random mixed integer programming model for the sustainable reverse logistics network of waste electronic equipment in an uncertain environment, and verified the effectiveness of the random model by solving the optimal solution. Pourjavad *et al*. [32] built a multi-echelon, multi-period fuzzy multi-objective mixed integer linear programming model based on the uncertainty of decision factors to study the degree of environmental and cost impact, and designed a non-dominant sorting genetic algorithm to solve the model. Dehghan *et al*. [33] proposed a robust fuzzy planning method for the closed-loop supply chain network of general edible oil, and verified the feasibility and effectiveness of the method in the case of mixed uncertainty of various parameters through simulation. Ghomi *et al*. [34] designs a closed-loop supply chain network multi-objective model considering random interruption and shortage, and meets customer demand by adopting different elastic strategies. Fakhrzad *et al*. [35] proposed a production-distribution fuzzy multi-objective programming method based on the green closed-loop supply chain to study how to reduce carbon emissions from vehicle movement under uncertain conditions. Santander *et al*. [36] constructed a mixed integer linear programming model for the 3D printing plastic closed-loop supply chain network. Through analysis, it can be known that this plastic recycling method can produce better environmental and economic benefits.

However, whether it is game theory or linear or nonlinear programming, we can see that there are still limitations in the study of closed-loop supply chain under the influence of uncertainty. These methods can only analyze the relationship between the system structure to study the influence of various uncertainties on the closed-loop supply chain in the current scenario or the future in a short time and provide various methods and suggestions for reducing such influence, but cannot study the development trend of the closed-loop supply chain system in the future for a long time from a long-term perspective.

Based on this analysis, the advantages of the system dynamics approach appear and are used by many scholars. From a long-term perspective, system dynamics is a discipline to study the relationship between the internal and external structures and elements of the system, and to solve the problems existing in the system from a long-term perspective. Taking agricultural waste as the research object, Zhao *et al*. [37] built a closed-loop supply chain system dynamics model, and simulated the model with carbon emission as the index, in order to improve the ecological efficiency of the closed-loop supply chain system. Goltsos *et al*. [38] explored how different fields and disciplines adapt to the performance of uncertainty in terms of supply, process, demand and control by building a closed-loop supply chain system dynamics model, and provided research ideas for enterprises. Based on the demand and return of the incentive dependence of the closed-loop supply chain, Zhao *et al*. [39] constructed a multi-stage closed-loop supply chain system dynamics model to study the benefits of the closed-loop supply chain system under the condition of providing incentives. Miao *et al*. [40] took waste e-waste as an example, constructs a dynamic model of a closed-loop supply chain system for mixed recycling, and determines the optimal proportion of recycling distribution among various main enterprises through simulation, thus improving the recovery rate of e-waste. Xue *et al*. [41] also took waste e-waste as an example and constructs a closed-loop supply chain system dynamics model dominated by retailers to study the impact of waste e-waste recovery in the closed-loop supply chain.

In addition, there are many other methods to study the closed-loop supply chain under uncertain environment. Huang *et al*. [42] proposed an uncertain representation method based on modal interval in the case of product quality uncertainty, and confirmed the effectiveness of this method in terms of collection strategy by comparing it with the traditional scenarie-based method. Sahebjamnia *et al*. [43] proposed a hybrid element heuristic algorithm based on the tire closed-loop supply chain network to find the optimal solution for the total cost of the closed-loop supply chain model. Zarbakhshnia *et al*. [44] also proposed a non-dominant sequencing genetic algorithm by building a sustainable closed-loop supply chain model to help solve the problem of carbon dioxide emission cost in the operation process of closed-loop supply chain. Michael *et al*. [45] developed a two-stage reverse supply chain multi-objective optimization model to study the performance of closed-loop supply chain in the case of uncertain supply and demand. By solving the model using the ε-constraint method, it was found that the model could promote the improvement of performance level of closed-loop supply chain.

Through the analysis of literature, it is found that although scholars have done a lot of research on the closed-loop supply chain in uncertain emergencies, they mainly analyze the performance of the closed-loop supply chain from the perspective of material flow, and seldom consider and analyze the capital flow of the main enterprises of the closed-loop supply chain [46-50]. In many cases, the hidden research hypothesis of the main enterprises of the closed-loop supply chain in the case of sudden uncertainty shows that the capital flow of enterprises will not be greatly affected, but this is greatly deviated from the actual situation. The capital flow of an enterprise not only directly determines the operation of a single manufacturer, but also affects the operation of other main manufacturers in the closed-loop supply chain. Therefore, the capital flow of the main enterprises in the closed-loop supply chain should not be ignored in the case of an uncertain emergency. Therefore, from the perspective of the coupling of material flow and capital flow in the closed-loop supply chain, this paper studies the short-term interruption of material flow in the closed-loop supply chain under the influence of COVID-19 epidemic, the impact on the fluctuations of all main enterprises in the closed-loop supply chain and the recovery of enterprises.

3. Construction of a closed-loop supply chain coupling system model

3.1 Causal analysis

Causal analysis is a way of showing the causal relationship between phenomena or things, and is an important part of system dynamics. Using Vensim simulation software, complex system relationships can be represented in a simple and clear way. Fig. 1 is the causal diagram of the closed-loop supply chain system.

M Inventory-M Delivery rate-R Inventory-R Sales rate-Weekly output of waste products-T Recovery-T Inventory-M Remanufacturing rate-MN Order rate-M Manufacturing rate-M Inventory. In the feedback loop, manufacturers' inventories will improve their delivery rate, and make the dealer inventories. Dealer inventory will increase their sales, increase the circulation of products on the market, further increase in the number of waste products will be produced per week, to reduce market pressure, recovery of chamber of commerce to increase recycling of waste products, thus recyclers inventories will make recyclers to provide manufacturers for remanufacturing product quantity increase, which will increase the rate of manufacturers of remanufacturing, new product remanufacturing rate increase would make manufacturers order rate is reduced. Lower order rate of new products will lead to lower manufacturing rate of manufacturers, and eventually lead to lower inventory of manufacturers.

M Capital-M New product manufacturing capacity-MN Order rate-M Manufacturing rate-M Inventory-M Delivery rate-R Inventory-R Sales rate-Weekly waste product production-T Recovery rate-T Inventory-M Remanufacturing rate-Remanufacturing cost-M Cost-M Capital. In the feedback loop, the funds would increase manufacturers on new product manufacturing capability, which will increase the rate of manufacturers order new products. New product order rate increase would lead to manufacturers manufacturing rate increases, and this will enable manufacturers inventories and shipping rates increased. Thereby sellers increase sales, and this will lead to increase in the number of market products, produce a large number of waste products, therefore improve the recovery rate of waste products recycling chamber of commerce, and lead to recyclers to raise the level of inventory. The increase in the inventory of recyclers will improve the quantity of products provided by recyclers to manufacturers for remanufacturing, which will enhance the remanufacturing rate and remanufacturing cost of manufacturers. Thus it will increase the production cost of products for manufacturers, and finally affects the capital level of manufacturers.

T Capital-T Recovery ability-T Recovery rate-T Product recovery cost-T Cost-T Capital. In this feedback loop, the improvement of the fund level of the recycler will encourage the recycler to have more money to recycle the waste products in the market, and improve its recovery capacity and recovery rate. The improvement of the recovery rate of waste products will increase the product recovery cost and overall cost of the recycler, and thus reduce the fund level of the recycler.

Similarly, the causal feedback relationship between M capital and R capital is similar to that of T capital. Due to the limited space of this article, too many details will not be described here.

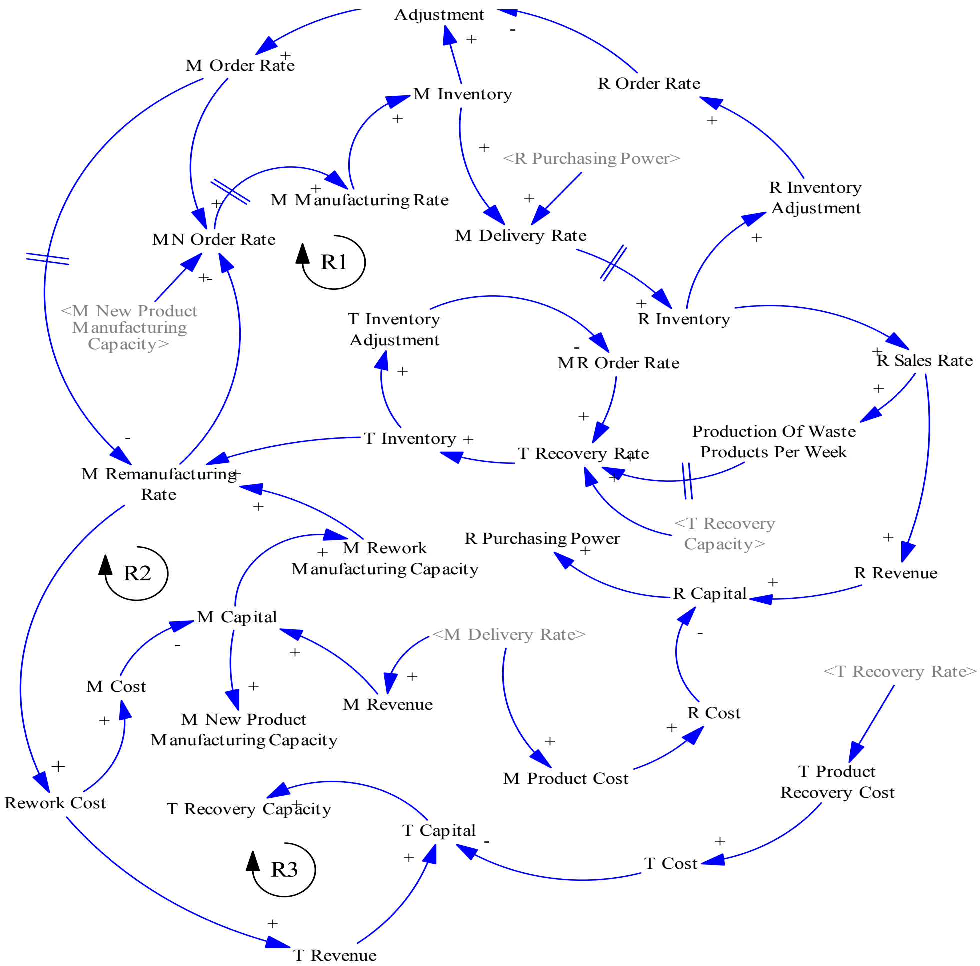

Fig. 1 Causal diagram of the closed-loop supply chain system

3.2 Construction of the system dynamic flow diagram model

According to the above causal relationship analysis diagram, it can be observed that there is a causal relationship between variables. By using Vensim simulation software and the principle of system dynamics, a closed-loop supply chain system flow diagram with the coupling of material flow and capital flow was constructed, which was divided into the material flow subsystem flow diagram and capital flow subsystem flow diagram, as shown in Fig. 2 and Fig. 3.

As can be seen from the flow diagram of the material flow subsystem in Fig. 2, the subsystem mainly simulates the flow of products between the main enterprises of the closed-loop supply chain and the changes of the inventory of each main enterprise. Among them, *M* Inventory, *R* Inventory and *T* Inventory are the state variables, which mainly reflect the inventory level of each main enterprise in the system. *M* manufacturing rate, *M* remanufacturing rate, *M* delivery rate, *R* sales rate and *T* recovery rate are rate variables, which mainly reflect the change rate of product inventory quantity of each main enterprise. *M* Ordering rate, *MN* Ordering rate, *R* Ordering rate, *C* Quantity demanded and *MR* Ordering rate are auxiliary variables. *M* Production delay, *M* Delivery delay, *M* Remanufacturing delay, *T* Recovery delay and so on are constant variables. In the material flow subsystem, manufacturers mainly engage in production activities by purchasing raw materials or recycled waste products from recyclers. According to the market demand, the seller determines its own order rate and issues order request to the manufacturer. The manufacturer sends the goods according to the seller's order. When the product is transported from the manufacturer’s warehouse to the seller's warehouse, the seller starts to sell the product to the market. After the end of the product life cycle in the market, waste products will be recovered by the recycler, who will sell the waste products recovered in the warehouse to the manufacturer for remanufacturing, so as to realize the circulation of products.

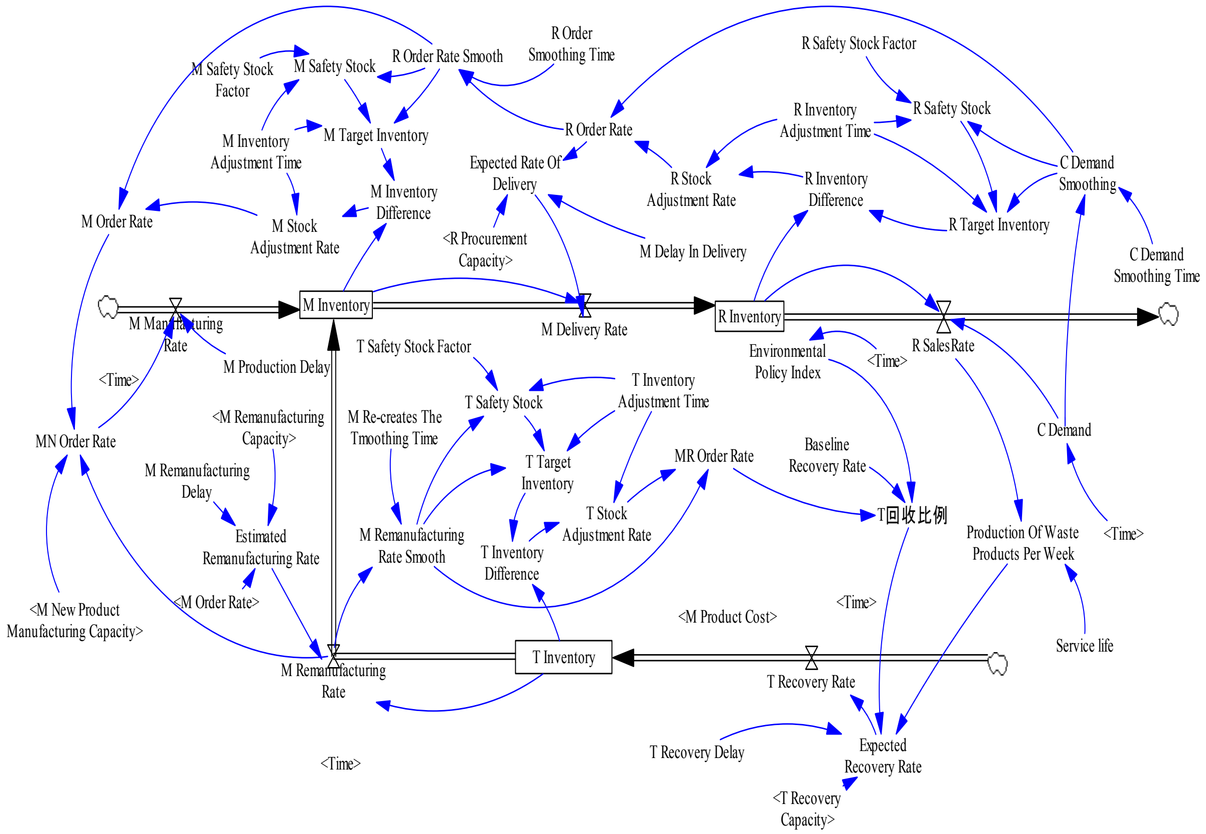

Fig. 2 Material flow subsystem flow diagram

It can be seen from the fund flow subsystem in Fig. 3 that this subsystem mainly simulates the change of the fund level of each main enterprise in the closed-loop supply chain. As the closed-loop supply chain system based on the coupling of material flow and capital flow is constructed in this paper, the subsystem is greatly affected by the material flow subsystem and changes with the change of material flow. In the subsystem of capital flow, the state variables mainly include *M* capital, *R* Capital and *T* Capital, which mainly reflect the capital status of each subject. Rate variables include *M* Cost and *M* Revenue, *R* Cost and *R* Revenue, *T* Cost and *T* Revenue, which mainly reflect the changes of cost and revenue of each main enterprise. *M* New product manufacturing capacity, *M* Reproduct manufacturing capacity, *R* Sales capacity, *T* Recovery capacity and so on are auxiliary variables; *M* Fixed expenditure, *R* Fixed expenditure, *T* Fixed expenditure and commodity depreciation rate are constant variables. In the fund flow subsystem, the manufacturer mainly generates costs by purchasing raw materials or waste products from recyclers and earns revenue by selling new products or reproduce to distributors. For sellers, the purchase of products from manufacturers is their cost expenditure, and their source of income is mainly obtained by selling products to the market. After the end of the product life cycle in the market, the recycler collects waste products and generates costs. After that, the recycler sells the recovered waste products to the manufacturer to obtain income. Manufacturers buy waste products from recyclers for remanufacturing, and the money start a new cycle. The capital of each main enterprise in the subsystem is mainly expressed as the difference between its income and cost. By analyzing the relationship between the income and cost of each main enterprise, the capital status of the enterprise is analyzed to realize the flow of capital in the closed-loop supply chain system.

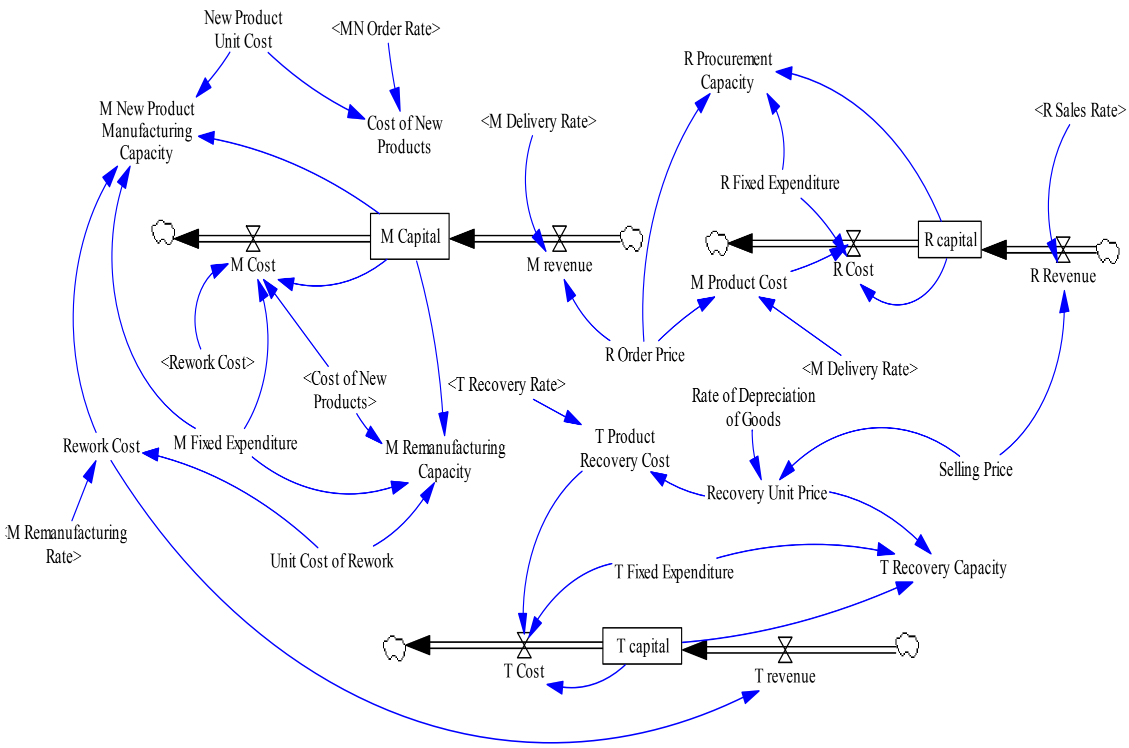

Fig. 3 Capital flows subsystem flow chart

3.3 Design of main model parameters and equations

Notations

Some variables are set in this paper, and the symbol setting is shown in Table 1.

Table 1 Symbol settings

Variable	Explain	Variable	Explain
M	Manufacturers	MN	The new product
R	Sellers	MR	Remanufactured product
T	Recyclers	C	Consumer demand
M_{sc}	M Safety stock coefficient	R_i	R Inventory
M_{it}	M Inventory adjustment time	R_{sr}	R sales rate
M_{pd}	M Production delay	R_{ss}	R Safety stock
M_{dd}	M Delay in delivery	T_s	T Stock
M_{rd}	M Remanufacturing delay	T_r	T Recovery
T_{rd}	T Recovery delay	M_r	M Recovery
T_{sc}	T Safety stock coefficient	R_r	R Recovery
T_{it}	T Inventory adjustment time	M_c	M Capital
B_r	Benchmark recovery ratio	T_c	T Capital
C_{rt}	C Requires smoothing time	R_c	R Capital
R_{sc}	R Safety stock coefficient	M_{co}	M Cost
R_{it}	R Inventory adjustment time	T_{co}	T Cost
M_i	M Inventory	R_{co}	R Cost
M_{rr}	M Remanufacturing rate	E_r	Expected remanufacturing rate
M_{mr}	M Manufacturing rate	T_i	T Inventory
M_{dr}	M Delivery rate	MN_o	MN Ordering rate
M_{ss}	M Safety stock	C_d	C Demand
rc	Rework cost	M_{fe}	M Fixed expenditure
nc	New product cost	M_{pc}	M Product cost
T_{pc}	T Product recovery cost	R_{fe}	R Fixed expenditure
w_p	Weekly waste product production	T_{fe}	T Fixed expenditure

Parameter setting

The main constant parameter settings in this model are shown in Table 2. Among them, M_{pd}, M_{dd}, M_{rd} and M_{rd} are all within a reasonable time, which conforms to the situation that there are some delays among all main enterprises in the closed-loop supply chain system under the normal social and economic environment. According to the relevant research of Professor Zhang Yuchun's team, [51] M_{sc} and T_{sc} are 0.2, R_{sc} is 0.3, T_{it} and R_{it} are 3, M_{it} is 5, B_r is 0.2, and C_{rt} is 3.

Table 2 Main constant parameter settings

Variable	Numerical	Variable	Numerical
M_{sc}	0.2	T_{sc}	0.2
M_{it}	5	T_{it}	3
M_{pd}	5	B_r	0.2
M_{dd}	1	C_{rt}	3
M_{rd}	3	R_{sc}	0.3
T_{rd}	2	R_{it}	3

Main equation design

In order to describe the impact and recovery of each entity in the closed-loop supply chain under the short-term interruption of material flow during COVID-19 outbreak, this paper simulated the model based on the original model data of Professor Zhang Yuchun and his team [51]. Through the above causal relationship analysis, the relationship between the variables in the model is clarified and the equation is constructed. Formula settings for the main variables are shown below.

$$M_i = \text{INTEG}\ (\text{MAX}\ (M_{rr} + M_{mr} - M_{dr}, 0));\ \text{Initial Value} = M_{ss} \tag{1}$$

$$R_i = \text{INTEG}\ (M_{dr} - R_{sr});\ \text{Initial Value} = R_{ss} \tag{2}$$

$$T_s = \text{INTEG}\ (\text{MAX}\ (T_r - M_{rr}, 0));\ \text{Initial Value} = T\ \text{Initial inventory Value} \tag{3}$$

$$M_c = \text{INTEG}\ (\text{MAX}\ (M_r - M_{co}, 0));\ \text{Initial Value} = 0 \tag{4}$$

$$R_c = \text{INTEG}\ (R_r - R_{co});\ \text{Initial Value} = 0 \tag{5}$$

$$T_c = \text{INTEG}\ (T_r - T_{co});\ \text{Initial Value} = 0 \tag{6}$$

$$M_{mr} = \text{DELAY3I}\ (\text{MAX}\ (MN_o, 0), M_{pd}, \text{Initial value 1}) \tag{7}$$

$$M_{rr} = \text{MIN}\ (E_r, T_i) \tag{8}$$

$$M_{dr} = \text{MIN}\ (M_i, \text{Expected delivery rate}) \tag{9}$$

$$R_{sr} = \text{MIN}\ (C_d, R_i) \tag{10}$$

$$M_{co} = \text{MIN}\ (M_c, M_{fe} + rc + nc) \tag{11}$$

$$M_r = M_{dr} \cdot R\ \text{Ordering unit price} \tag{12}$$

$$R_{co} = \text{MIN}\ (R_c, M_{pc} + R_{fe}) \tag{13}$$

$$R_r = R_{sr} \cdot \text{Sales unit price} \tag{14}$$

$$T_{co} = \text{MIN}\ (T_c, T_{pc} + T_{fe}) \tag{15}$$

$$T_r = rc;\ C_d = (\text{RANDOM UNIFORM}\ (5000, 7000, 0) + 3000 \cdot Time \tag{16}$$

4. Simulation and results

The relevant settings of this model are as follows: INITIAL TIME = 0; FINAL TIME = 300; TIME STEP = 1, that is, the initial TIME of model simulation is 0, the end TIME is 300, and the simulation TIME STEP is 1. In this paper, the Vensim simulation software is mainly used to model and simulate, and the model inspection and unit inspection functions inherent in the software are used to test and verify the model, so as to realize the real reproduction of the real closed-loop supply chain system in the simulation software.

4.1 Original base scenario

Closed-loop supply chain is the organic unity of the forward supply chain and reverse supply chain. Its existence promotes the circulation flow of products from production to sales, and then to recycling and remanufacturing. However, when COVID-19 outbreak occurs, all kinds of delays in the closed-loop supply chain will increase, and the circulation flow of products within the system will be affected, and the operation of major enterprises will also be severely hit. Based on this, 5 scenarios were set up to simulate the response of the closed-loop supply chain in the case of COVID-19 outbreak. The 5 scenarios are the original baseline scenario, the burst base scenario, the burst-recovery time for 10 weeks scenario, the burst-recovery time for 20 weeks scenario, and the burst-recovery time for 30 weeks scenario. Various delay time settings under different situations are shown in Table 3.

Table 3 Various delay times under different situations

Scenario	M_{pd}	M_{dd}	M_{rd}	T_{rd}
Original baseline scenario	5	1	3	2
Burst base scenario	10	6	8	7
Burst-Recovery time 10 weeks scenario	10	6	8	7
Burst-Recovery time 20 weeks scenario	10	6	8	7
Burst-Recovery time 30 weeks scenario	10	6	8	7

Original baseline scenario

Original baseline scenario mainly simulates the normal social economic environment closed-loop supply chain enterprises' operation and subjects to the closed-loop supply chain system under this situation was not affected by the presence of COVID-19 outbreak, each kind of delay time to keep within a reasonable time range, is set to M_{pd} for 5 weeks, M_{dd} for 1 week, M_{rd} for 3 weeks and T_{rd} for 2 weeks. At the same time, under the original baseline scenario, the manufacturer's manufacturing rate and remanufacturing rate as well as the recovery rate of waste products of the recycler are relatively stable. The specific variable formula is designed as follows.

$$M_{mr} = \text{DELAY3I (MAX (}MN_o\text{, 0), }M_{pd}\text{, Initial value 1)} \tag{17}$$

$$M_{rr} = \text{MIN (}E_r,\ T_i) \tag{18}$$

$$T_r = \text{Expected recovery} \tag{19}$$

Burst base scenario

The burst base scenario is mainly to simulate the impact of the main enterprises in the closed-loop supply chain system when COVID-19 outbreak occurs. In this scenario, the material flow of the closed-loop supply chain begins to be interrupted from the COVID-19 outbreak at week 120 for a duration of 10 weeks, and all kinds of delay times are increased by 5 weeks under the influence of the outbreak. When the interruption ends, the delay time returns to normal until the end of the model operation. The specific variable formula is designed as follows.

$$\begin{aligned}M_{mr} = {} & \text{IF THEN ELSE (}Time < 120\text{, DELAY3I (MAX (}MN_o\text{, 0), }M_{pd}\text{, Initial value 1),}\\ & \text{IF THEN ELSE (}Time > 130\text{, DELAY3I (MAX (}MN_o\text{, 0), }M_{pd}\text{, Initial value 1), 0))}\end{aligned} \tag{20}$$

$$M_{rr} = \text{IF THEN ELSE (}Time < 120\text{, MIN (}E_r, T_s\text{), IF THEN ELSE (}Time > 130\text{, MIN (}E_r,\ T_s\text{), 0))} \tag{21}$$

$$T_r = \text{IF THEN ELSE (}Time < 120,\ E_r\text{, IF THEN ELSE (}Time > 130\text{, Expected recovery, 0))} \tag{22}$$

$$M_{pd} = \text{IF THEN ELSE (}Time < 120\text{, 5, IF THEN ELSE (}Time > 130\text{, 5, 10))} \tag{23}$$

$$M_{dd} = \text{IF THEN ELSE (}Time < 120\text{, 1, IF THEN ELSE (}Time > 130\text{, 1, 6))} \tag{24}$$

$$M_{rd} = \text{IF THEN ELSE (}Time < 120\text{, 3, IF THEN ELSE (}Time > 130\text{, 3, 8))} \tag{25}$$

$$T_{rd} = \text{IF THEN ELSE (}Time < 120\text{, 2, IF THEN ELSE (}Time > 130\text{, 2 , 7))} \tag{26}$$

Burst-Recovery time 10 weeks scenario

Burst-Recovery time 10 weeks scenario on the closed-loop supply chain system in the burst base scenario on the basis of further research, the situation is not only assume 120 weeks to 130 weeks between the closed-loop supply chain system due to short-term disruptions COVID-19 outbreak material flow, considerate and hypothesis from the 130-th to 140-th week between 10 weeks of recovery, at the same time affected by the epidemic, increase 5 weeks of delay time starting from the interrupt, continue to the end of the recovery period. The specific variable formula is designed as follows.

$$M_{pd} = \text{IF THEN ELSE } (Time < 120, 5, \text{IF THEN ELSE } (Time > 140, 5, 10)) \tag{27}$$

$$M_{dd} = \text{IF THEN ELSE } (Time < 120, 1, \text{IF THEN ELSE } (Time > 140, 1, 6)) \tag{28}$$

$$M_{rd} = \text{IF THEN ELSE } (Time < 120, 3, \text{IF THEN ELSE } (Time > 140, 3, 8)) \tag{29}$$

$$T_{rd} = \text{IF THEN ELSE } (Time < 120, 2, \text{IF THEN ELSE } (Time > 140, 2 , 7)) \tag{30}$$

Burst-Recovery time 20 weeks scenario

Burst-Recovery time 20 weeks scenario is also studied on the basis of the burst base scenario, which differs from the burst-recovery time 10 weeks scenario mainly in the material flow recovery period. In this scenario, the material flow recovery period is longer, from 130 to 150 weeks, and the recovery period is 20 weeks. At the same time, the duration of all kinds of delay time increase in the closed-loop supply chain system is 10 weeks longer than the previous scenario, and other relevant scenario settings are the same. The specific variable formula is designed as follows.

$$M_{pd} = \text{IF THEN ELSE } (Time < 120, 5, \text{IF THEN ELSE } (Time > 150, 5, 10)) \tag{31}$$

$$M_{dd} = \text{IF THEN ELSE } (Time < 120, 1, \text{IF THEN ELSE } (Time > 150, 1, 6)) \tag{32}$$

$$M_{rd} = \text{IF THEN ELSE } (Time < 120, 3, \text{IF THEN ELSE } (Time > 150, 3, 8)) \tag{33}$$

$$T_{rd} = \text{IF THEN ELSE } (Time < 120, 2, \text{IF THEN ELSE } (Time > 150, 2 , 7)) \tag{34}$$

Burst-Recovery time 30 weeks scenario

Burst-Recovery time 30 weeks scenario is similar to the previous two scenarios, except for the difference in the recovery period. In this scenario, the recovery cycle of material flow is 30 weeks, from 130 to 160 weeks. The longer the delay time, the longer the phenomenon lasts. The settings for other scenarios are the same. The specific variable formula is designed as follows.

$$M_{pd} = \text{IF THEN ELSE } (Time < 120, 5, \text{IF THEN ELSE } (Time > 160, 5, 10)) \tag{35}$$

$$M_{dd} = \text{IF THEN ELSE } (Time < 120, 1, \text{IF THEN ELSE } (Time > 160, 1, 6)) \tag{36}$$

$$M_{rd} = \text{IF THEN ELSE } (Time < 120, 3, \text{IF THEN ELSE } (Time > 160, 3, 8)) \tag{37}$$

$$T_{rd} = \text{IF THEN ELSE } (Time < 120, 2, \text{IF THEN ELSE } (Time > 160, 2 , 7)) \tag{38}$$

4.2 Analysis of the impact of manufacturer changes

It can be seen from Fig. 4 that the manufacturer's inventory changes were relatively stable under the burst base scenario. Under the burst base scenario, the manufacturer's inventory began to decline from the short-term interruption of COVID-19 outbreak material flow in week 120 to zero, followed by a sharp rise, peaked at week 141, then began to decline sharply, and gradually returned to normal after a small fluctuation. At the same time, it can be observed in the figure that when the recovery period is 10 weeks, 20 weeks and 30 weeks, there is a lag in the time when the manufacturer inventory reaches its peak.

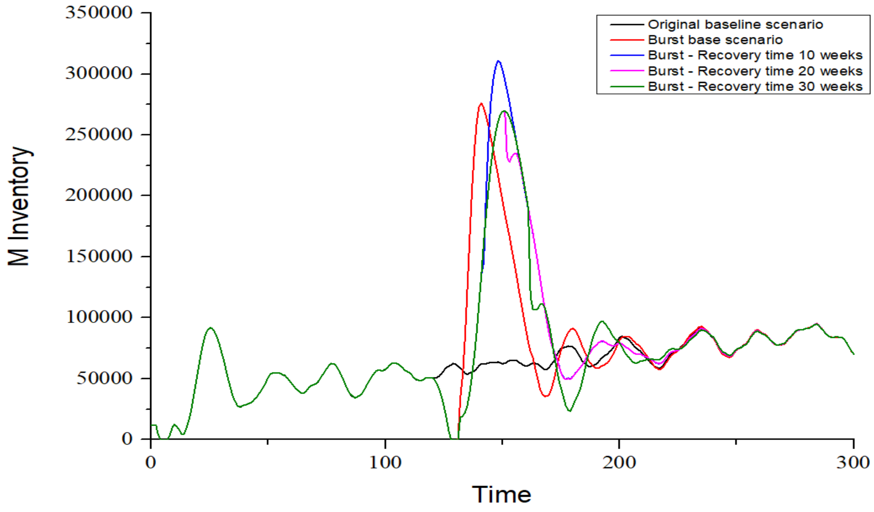

Fig. 4 Changes of *M* inventory under different scenarios.

Fig. 5 shows the variation of manufacturer's revenue under different scenarios. It can be observed in the figure that, compared with the original baseline scenario, when COVID-19 outbreak occurred, the manufacturer's revenue showed a downward trend under the base scenario and the outbreak-recovery period of 10 weeks, 20 weeks and 30 weeks, respectively. After the end of the epidemic, the manufacturer's income in the burst base scenario rose sharply, reached its peak in the 133rd week, then began to decline and gradually returned to normal, while the time of the outbreak and recovery was 10 weeks, 20 weeks and 30 weeks respectively. The time when the manufacturer's income began to rise and reached its peak showed different lags. At the same time, it can be seen from the figure that the peak value of the manufacturer's revenue in the burst-recovery period of 10 weeks, 20 weeks and 30 weeks is higher than that in the burst base scenario.

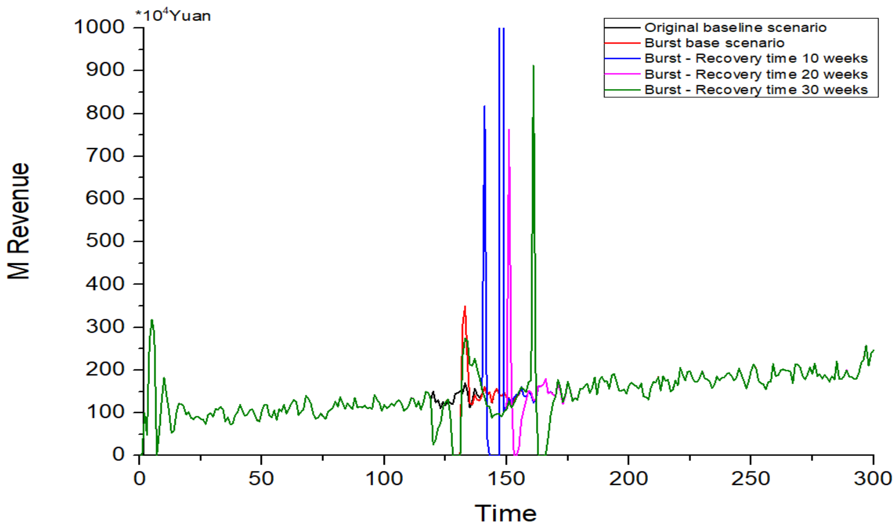

Fig. 5 Changes of *M* income under different scenarios

4.3 Analysis of the impact of seller changes

As can be seen from Fig. 6, compared with the original baseline scenario, under the burst base scenario, retailer stocks began to decline from the short-term interruption of COVID-19 epidemic material flow, and began to rise and return to normal after the outbreak. However, under the circumstances of 10 weeks, 20 weeks, and 30 weeks of the emergency-recovery period, the seller's inventory began to increase significantly after the end of the recovery period, but the inventory level began to rise at different times under different circumstances.

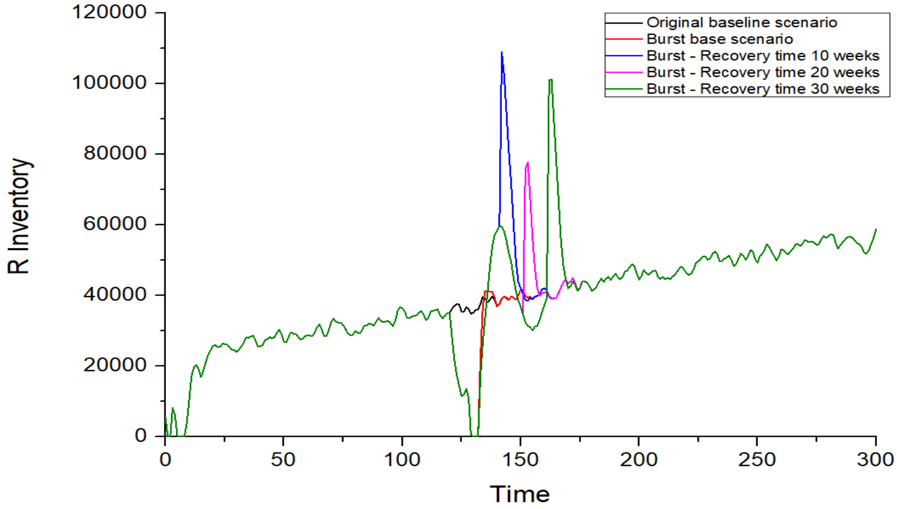

Fig. 6 Changes of *R* inventory under different scenarios

Fig. 7 shows that compared with the original baseline scenario, although the seller capital in the burst base scenario and convalescence respectively for 10 weeks, 20 weeks, 30 weeks scenario, in short-term COVID-19 outbreak phase material flow interruption of a slight decline, but generally speaking, the capital level of sellers fluctuates relatively uniformly.

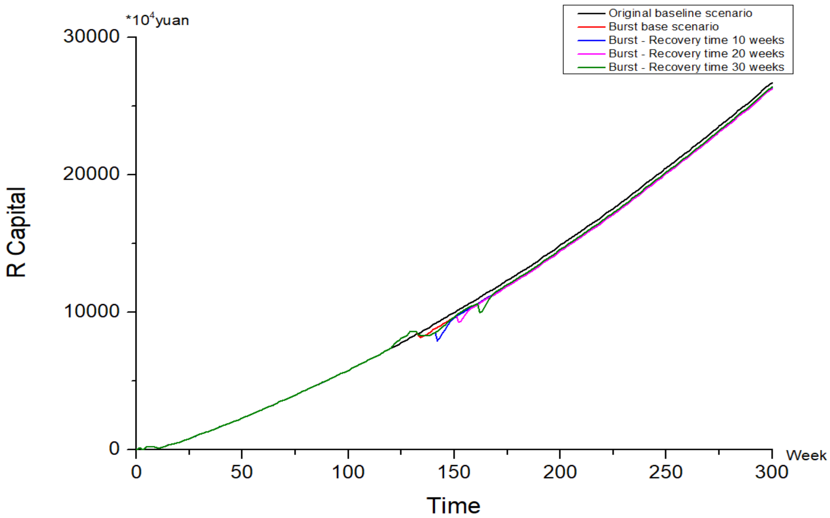

Fig. 7 Changes of *R* funds under different scenarios

4.4 Analysis of the impact of changes in recyclers

As can be seen from Fig. 8, under the burst base scenario, the inventory changes of recyclers are relatively stable and show an upward trend. But in the burst base scenario, when short-term COVID-19 outbreak material flow is interrupted, dealer inventory levels after balance short, began to decline and volatility, starting from the 138-th week inventory increase and keep nearly 20 weeks of steady state, after the stock has fallen dramatically, after several fluctuations gradually returned to normal. At the same time, it can be observed in the figure that when the recovery period is 10 weeks, 20 weeks and 30 weeks respectively, the inventory level of sellers will change significantly. In addition to lagging behind the burst base scenario in terms of change time, the most obvious change is that the inventory level in the recovery period scenario is significantly higher than that in the burst base scenario.

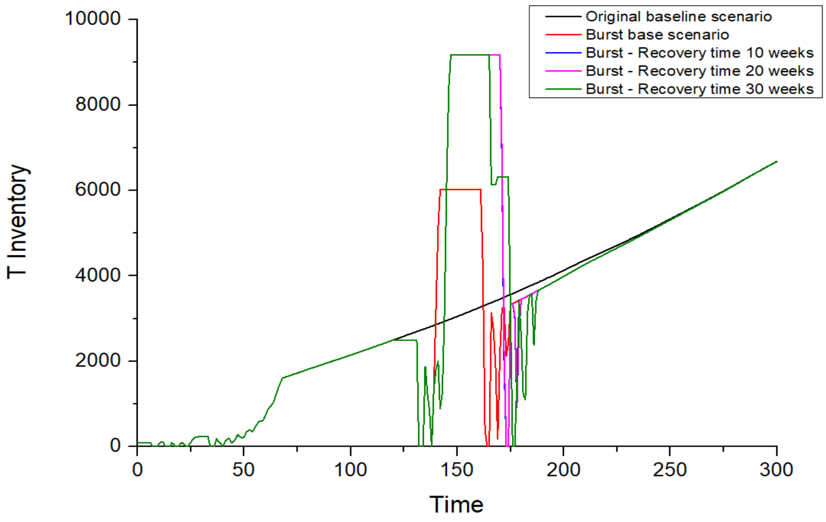

Fig. 8 Changes of *T* inventory under different scenarios

It can be seen from Fig. 9 that the funds of recyclers have the most obvious changes compared with the funds of manufacturers and sellers. When the material flow of the COVID-19 outbreak is interrupted for a short period, the recycler's funds do not rise and remain at a relatively stable level. Starting from week 160, the funds start to rise, which is similar to the tendency of the fund level under the original baseline scenario, but the fund level is lower than the original baseline scenario until the end of the model operation. At the same time, when recovery for 10 weeks, 20 weeks, respectively at 30 weeks, vendors for capital movements and burst base scenario changes is roughly same, but due to the existence of the recovery time and recovery time is different, began from 160 weeks in sellers money difference, the longer the recovery time, rise time, the lag of funds, the lower the capital levels.

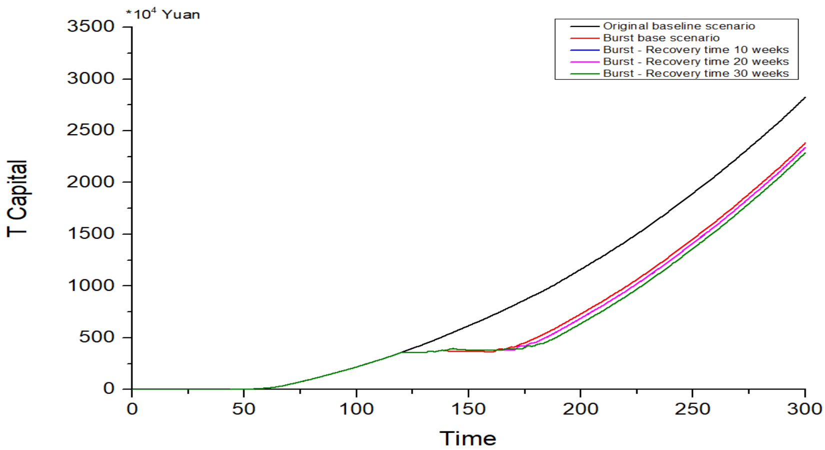

Fig. 9 Changes of *T* funds under different scenarios

5. Discussion

Through the closed-loop supply chain model simulation results, it can be seen that the changes of material flow related factors are more obvious than those of value flow related factors, especially the outbreak and recovery stage of COVID-19 epidemic. When COVID-19 outbreaks occur, inventory levels are significantly lower in the outbreak phase, whether for manufacturers, vendors, or recyclers. This was mainly due to the outbreak of the epidemic, manufacturers in the closed-loop supply chain system stopped production, and manufacturers reduced their production activities, so that their inventories were significantly reduced or even to zero. The inventory level of the manufacturer decreases, so that the quantity of goods that the seller buys from the manufacturer decreases, and the inventory level of the seller also drops sharply. Dealer inventory levels to reduce the decrease in the number of sales made to the market to sell products, the decrease in the number of the circulation of products on the market, a week will reduce the number of waste products. This makes the recyclers recycling to reduce the number of waste products from the market, causing recyclers inventories fell likewise, further affect the manufacturer.

In the recovery phase after the epidemic, the inventory level of all major enterprises increased significantly. This is mainly because manufacturers, in order to make up for the losses during the epidemic period, resumed production capacity as soon as possible and began to increase their own production activities, which caused a huge impact on the inventory and showed a significant increase. In order to make up for the loss, the seller will increase the purchase order volume, the inventory level also appears the sharp rise, the quantity of products sold to the market increases. More products in circulation on the market, the more waste products will be produced. In order to recover their own operations as soon as possible, recyclers recycle a large number of waste products from the market, which also brings a huge impact on inventory, and thus affects manufacturers.

With the increase of operation time, the COVID-19 epidemic has less and less impact on the main enterprises of the closed-loop supply chain, and the inventory of the main enterprises also starts to gradually return to the normal level.

At the same time, it can also be found from the simulation results that the influence of recyclers in the closed-loop supply chain system is obviously greater than the change of manufacturers and distributors. Mainly because the collector is different from the manufacturers and sellers, sellers when expanding sales, increased numbers of the product to circulate on the market, because the life cycle of the products is different, become a waste product of the time is not the same, and the cargo is handled by recyclers the recycling of waste products from the market, recyclers are not only affected by COVID-19 outbreak also influenced by the product itself, the most obvious, so changes in the recyclers are also the most far-reaching.

6. Conclusion

In this paper, the closed-loop supply chain system is analyzed from the coupling angle of material flow and capital flow, and the system dynamics simulation model of closed-loop supply chain system is built. In the context of the COVID-19 epidemic, the closed-loop supply chain system dynamics simulation model was constructed to simulate the affected situation of each main enterprise in the context of short-term material flow interruption of the closed-loop supply chain. Through the model analysis, the following conclusions can be drawn:

In the study of closed-loop supply chain, in addition to studying the change of material flow, it is also necessary to consider the change of capital flow associated with material flow. Since this paper mainly studies the coupling of material flow and capital flow, and such coupling situation has the influence feedback relationship between flows, it is necessary to choose a suitable research tool, and system dynamics is exactly the tool that can realize the coupling transfer influence relationship between the two flows.

The integrated model results can be seen, when COVID-19 outbreak short-term disruptions caused by material flow, different delay time to produce a great impact on the closed-loop supply chain enterprises are different subjects, but can be found that the main body of the enterprise financial conditions are relatively stable, the most obvious change of every main body enterprise inventory level.

On the whole, when the material flow of the COVID-19 outbreak is interrupted for a short period, regardless of the scenario, recyclers in the main enterprises of the closed-loop supply chain are most affected, indicating that recyclers are most affected by the COVID-19 outbreak and have a weak ability to cope with the uncertainty of the external environment.

Based on the conclusions drawn from the above analysis of the closed-loop supply chain system dynamics model, this paper proposes the following suggestions:

(1) In the context of COVID-19 outbreak, attention should be paid not only to the impact of material flow interruption on the closed-loop supply chain, but also to the impact of material flow recovery after the interruption on the inventory and capital of all main enterprises in the closed-loop supply chain.

(2) As far as the main enterprises of the closed-loop supply chain are concerned, recyclers are the most affected by the COVID-19 epidemic and have the weakest anti-risk capability. Therefore, in the three main enterprises of the closed-loop supply chain system in this paper, more attention should be paid to the recyclers, so as to ensure the stable operation of recyclers and maintain the normal operation of the closed-loop supply chain system.

In this paper, by using system dynamics under the influence of the Vensim software to build COVID-19 outbreak of closed-loop supply chain system model has universality, can be applied to other cases study of closed-loop supply chain, but the incident itself should be considered when applying the model, the characteristics of emergency and the impact on the closed-loop supply chain for scenario settings.

Author contributions

Conceptualization: Wei, Duan; Methodology: Wei, Duan and Hui, Ma; Validation: Wei, Duan, Desheng, Xu and Hui, Ma.; Writing – original draft preparation: Hui, Ma; Writing – review and editing: Wei, Duan, Desheng, Xu and Hui, Ma. All authors have read and agreed to the published version of the manuscript.

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A dynamic job-shop scheduling model based on deep learning

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A B S T R A C T

Ideally, the solution to job-shop scheduling problem (JSP) should effectively reduce the cost of manpower and materials, thereby enhancing the core competitiveness of the manufacturer. Deep learning (DL) neural networks have certain advantages in handling complex dynamic JSPs with a massive amount of historical data. Therefore, this paper proposes a dynamic job-shop scheduling model based on DL. Firstly, a data prediction model was established for dynamic job-shop scheduling, with long short-term memory network (LSTM) as the basis; the Dropout technology and adaptive moment estimation (ADAM) were introduced to enhance the generalization ability and prediction effect of the model. Next, the dynamic JSP was described in details, and three objective functions, namely, maximum makespan, total device load, and key device load, were chosen for optimization. Finally, the multi-objective problem of dynamic JSP scheduling was solved by the improved multi-objective genetic algorithm (MOGA). The effectiveness of the algorithm was proved experimentally.

A R T I C L E   I N F O

Keywords:
Long short-term memory (LSTM);
Dynamic job-shop scheduling;
Multi-objective genetic algorithm (MOGA);
Adaptive moment estimation (ADAM)

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1. Introduction

With the advent of the new industrial era, the old production model has gradually been replaced by the flexible, highly integrated, and automated production model of modern intelligent manufacturing. In modern intelligent manufacturing, the production process focuses on the coordination and balance of various links, such as production, supply, sales, transportation, and storage, and attaches equal importance to economic benefits as well as the efficiency, quality, and safety of production [1-4].

The rational allocation of job-shop resources can effectively reduce manpower and material costs of manufacturers. To enhance its core competitiveness, every manufacturer needs to look for an effective way to solve the job-shop scheduling problem (JSP) [5-8]. In actual production, the processing performance is greatly affected by various uncertainties and instabilities. Therefore, it is urgent to solve the job-shop scheduling model under disturbance factors.

The JSP is mostly solved by evolutionary algorithms, swarm optimization algorithms, and artificial intelligence algorithms. The optimal solution is usually obtained through iterations and group search, with the aim to minimize the makespan and energy consumption [9-13]. Shokouhi

[14] classified the dynamic events in actual production process into four categories according to processing strategies and processes, namely, addition events, device occupation events, delayable events, and exchangeable events, provided the mathematical model and constraints for two typical dynamic times (i.e., device failure and early delivery), and solved the dynamic JSP with the adaptive genetic algorithm. Somashekhara *et al*. [15] introduced the local search algorithm to speed up the discrete PSO, and designed a task-driven rolling window scheduling strategy to cope with the dynamic events like the shutdowns caused by device failure, order placement, and order cancelation. Shahrabi *et al*. [16] analyzed the properties of three typical dynamic JSPs, including the shutdown caused by staged arrival of single workpieces, that caused by staged arrival of workpiece batches, and that caused by device failure, designed a scheduling simulation test with the scheduling rules as independent variables, and verified that the genetic algorithm with adaptive variable neighborhood search is feasible and effective in solving these dynamic JSPs. Gondran *et al*. [17] explored the JSP under the background of multi-agent technology application: the multi-agent collaboration contract network protocol was improved to control the excessively high traffic and increase the cooperation efficiency; then, a job-shop scheduling model was constructed for multiple agents and objectives and specific constraints; finally, the performance of the adaptive PSO in solving the JSP was tested.

The traditional genetic algorithm and its improvements face several problems in optimizing job-shop scheduling plans: slow convergence, lack of population diversity, and proneness to local optimum trap [18-20]. From the perspectives of parallel structure and multiple swarms, Marzouki *et al*. [21] constructed a modularized dynamic job-shop scheduling model, which contains a dynamic database module, a genetic algorithm module, and a re-scheduling program application module; their model integrates the advantages of the elite population protection strategy in the hierarchical evaluation system in improving crossover and mutation probabilities. Keddari *et al*. [22] adopted bee colony optimization to improve a solving algorithm for the multi-objective JSP in actual production. Reddy *et al*. [23] adopted the improved weed algorithm to deal with the multi-objective JSP, with device load, unit device load, and scheduling cycle as optimization goals.

Many have conducted valuable research into the dynamic JSP in actual production process [24-26]. Danielsson *et al*. [27] combined demand prediction with scheduling plan to build a neural network-based prediction model for manhour realization rate, and applied intelligent group optimization algorithm to optimize the multiple objectives in job-shop scheduling and stabilize the manhour realization rate. Teymourifar *et al*. [28] integrated second-order oscillation with optimal network-bandwidth allocation (ONBA) algorithm to obtain the scheduling data of dynamic job-shop model, and greatly shortened the prediction time by improving the learning rate of deep learning (DL) network. Facing the optimization of multiple objectives, resource scheduling in cloud manufacturing extends the time to solve cloud manufacturing tasks. To solve the problem, Teymourifar *et al*. [28] improved the ONBA algorithm by differential evolution algorithm to obtain the scheduling data of the cloud manufacturing model. The data were applied to train the improved deep belief network (IDBN). The learning rate of DL was improved to realize rapid prediction of the scheduling results of cloud manufacturing model. Experimental results show that their method can accurately predict the scheduling results, and shorten the scheduling time, opening a new path to multi-objective group optimization.

In summary, the existing algorithms for dynamic JSP boast strong applicability, and good optimization effect. However, they often converge to the local minimum, and behave stochastically. Compared with traditional shallow neural networks, DL neural networks are excellent in handling complex dynamic JSPs with a huge amount of historical data. Therefore, the authors developed a dynamic job-shop scheduling model based on DL.

In the following parts of the paper: Section 2 establishes a data prediction model for dynamic job-shop scheduling based on long short-term memory network (LSTM), and improves the generalization and prediction performance of the model by Dropout technology and adaptive moment estimation (ADAM). Section 3 describes the dynamic JSP in details, chooses three objective functions, namely, maximum makespan, total device load, and key device load, and constructs the corresponding mathematical model. Based on the predicted data on dynamic job-shop scheduling obtained in Section 2, Section 4 improves the multi-objective genetic algorithm (MOGA) to handle the multi-objective dynamic JSP, and describes the improved MOGA. Section 5 verifies the effectiveness of the improved MOGA in solving dynamic JSP. Section 6 summarizes the findings of this research.

2. Data prediction model

As a multi-layer representation learning algorithm, DL has a deeper network structure, solves more complex problems, and achieves better prediction accuracy, than ordinary neural networks. The LSTM can effectively overcome the vanishing or exploding gradients of traditional DL neural networks. Fig. 1 illustrates the structure of the LSTM. The typical feature of the LSTM is that the hidden layer nodes are replaced with a storage unit, and four modules, i.e., input door, control door, forget door, and output door, are added to the conventional recurrent neural network.

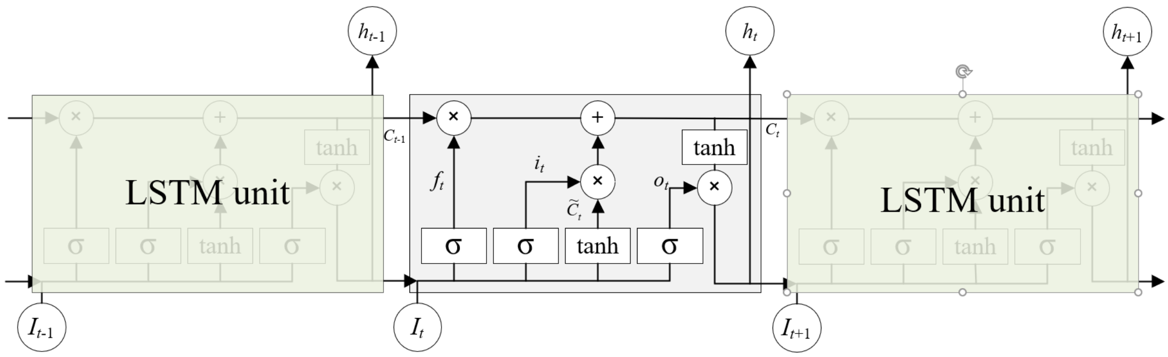

Fig. 1 Structure of the LSTM

Let C_{t-1} be the output of the control door at time $t-1$, which reflects whether to discard the current data; W_i, W_f, W_C, and W_o be the coefficient matrices of input door, forget door, control door, and output door, respectively; σ be the nonlinear activation function sigmoid. Then, the output of the forget door can be calculated by:

$$f_t = \sigma\left(W_f \cdot [h_{t-1}, I_t] + \varepsilon_f\right) \tag{1}$$

The input door determines which data to be updated by the LSTM cell. The output of the input door can be calculated by:

$$i_t = \sigma(W_i \cdot [h_{t-1}, I_t] + \varepsilon_i) \tag{2}$$

The new candidate value vector can be created by the tanh function:

$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, I_t] + \varepsilon_C) \tag{3}$$

The control door determines which data to be updated by the LSTM cell. The value of C_t can be calculated by:

$$C_t = f_t \cdot c_{t-1} + i_t \cdot \tilde{C}_t \tag{4}$$

The output door completes the state update of the LSTM cell, and its output can be calculated by:

$$o_t = \sigma(W_o \cdot [h_{t-1}, I_t] + \varepsilon_o) \tag{5}$$

The input of LSTM cell at time t can be expressed as:

$$h_t = o_t \cdot \tanh(C_t) \tag{6}$$

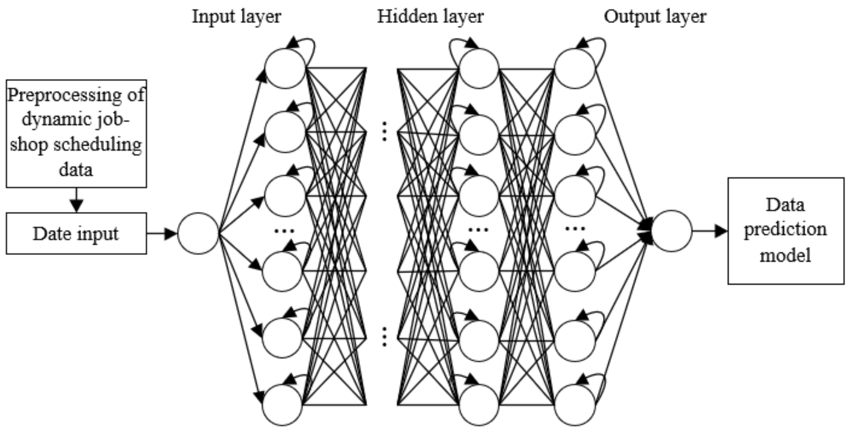

Fig. 2 LSTM-based data prediction model for dynamic JSP

In a DL network model, the parameters will increase exponentially with the increase of network layers and that of layer nodes. The exponential increase of parameters will weaken the generalization ability and prediction performance of the model, increasing the probability of overfitting.

This problem was solved by the Dropout technology. Firstly, half of the hidden layer nodes in the network were randomly chosen, and their inputs and outputs were set to zero. Then, the input I was propagated forward through the new network, and the resulting loss was propagated backward through the network. After some training samples completed the above process, the weights and errors of nodes in the hidden layer, whose inputs and outputs had not been set to zero, were updated by stochastic gradient descent. Then, the nodes whose inputs and outputs had been set to zero were restored. After that, half of the hidden layer nodes in the new network were randomly chosen, and their inputs and outputs were set to zero. This process was repeated again and again. Fig. 3 shows the network structure improved by the Dropout technology.

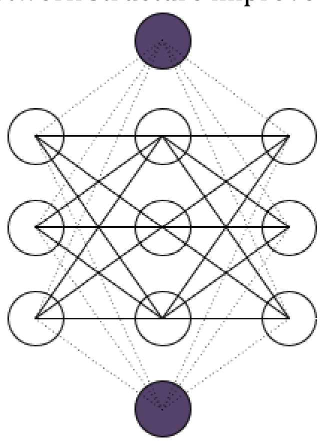

Fig. 3 Network structure improved by the Dropout technology

The learning rate α greatly affects the training efficiency of the network. To boost the efficiency, the key is to improve the adaptivity of the learning rate to the network. In this paper, the ADAM is selected to iteratively compute the gradient of the loss function, and to further update network parameters. Let θ_0 be the initial parameter vector. If parameter θ_t does not converge at time t, then make $t = t + 1$, and obtain the gradient for the new iteration by:

$$g_t = \nabla_\theta f_t(\theta_{t-1}) \tag{7}$$

The first moment vector can be updated by:

$$m_t = \beta_1 m_{t-1} + (1 - \beta_1) g_t \tag{8}$$

where, β_1 is the exponential decay rate of the first moment estimates. The second moment vector can be updated by:

$$v_t = \beta_2 v_{t-1} + (1 - \beta_2) g_t^2 \tag{9}$$

where, β_2 is the exponential decay rate of the second moment estimates. The calculation deviations for the first and second moment vectors can be updated by:

$$\begin{cases} \widehat{m}_t = \dfrac{m_t}{1 - \beta_1^t} \\ \hat{v}_t = \dfrac{v_t}{1 - \beta_2^t} \end{cases} \tag{10}$$

The network parameters can be updated by:

$$\theta_t = \theta_{t-1} - \frac{\alpha \cdot \widehat{m}_t}{\sqrt{\hat{v}_t + b}} \tag{11}$$

where, b is a small constant that prevents the denominator from being zero.

Fig. 4 presents our data prediction model of dynamic job-shop scheduling. The data prediction model is constructed through the following steps based on the deep LSTM:

Step 1: Design the node structure on each layer, and randomly initialize network parameters.
Step 2: Initialize the data on dynamic job-shop scheduling, and divide the vectorized data samples into training and test sets at a certain ratio. During the training, the network loss is calculated through forward propagation as that in backpropagation (BP) neural network, and the network parameters are updated iteratively through ADAM.
Step 3: Import the test samples into the trained model, which outputs the predicted data on dynamic job-shop scheduling.

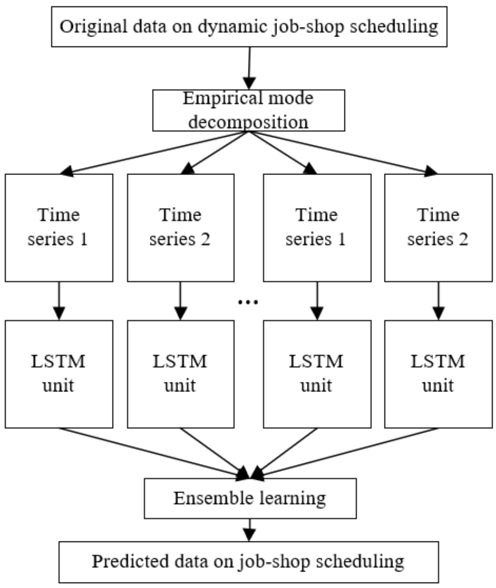

Fig. 4 Structure of the data prediction model

3. Problem description and mathematical modeling

Fig. 5 shows the distribution of processes in the scheduling data on a dynamic car-making job-shop. It can be seen that each workpiece in the dynamic job-shop contains one or more preset processes that can be implemented on different devices. The scheduling performance of the entire production system can be optimized by assigning the ideal device to each process, and ensuring that the processes on each device is sorted in the best possible manner.

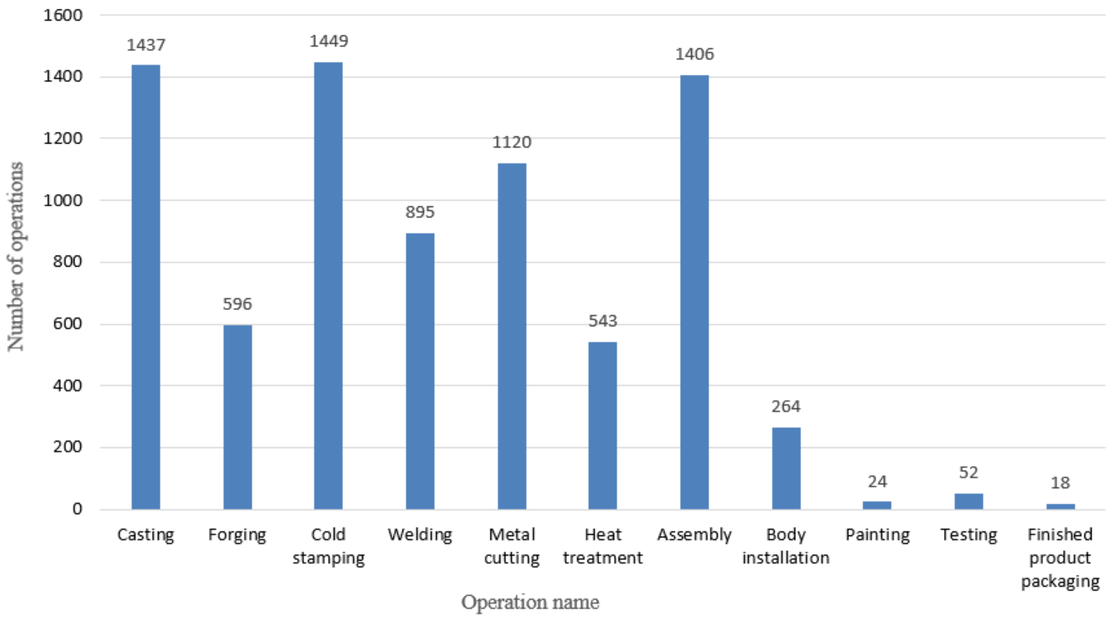

Fig. 5 Distribution of processes in the scheduling data on a dynamic car-making job-shop

Suppose the job-shop has N workpieces A_i to be processed, $i = 1, 2, \ldots, N$, where the i-th workpiece A_i involves N_i processes P_k, $k = 1, 2, \ldots, N_i$, and M devices E_j, $j = 1, 2, \ldots, M$. Let E_{ij} be the set of devices suitable for implementing the k-th process P_{ik} of workpiece A_i, and T_{ijk} be the time required to implement process P_{ik} on the i-th device E_j. Then, the sum of processes for all N workpieces can be expressed as:

$$P_{TOTAL} = \sum_{i=1}^{N} N_i \tag{12}$$

The production cycle of workpieces is greatly affected by the maximum makespan, and the overall utilization of devices in the dynamic job-shop depends largely on device load. Under these constraints, this paper decides to optimize three objective functions: maximum makespan, total device load, and key device load. Among them, the maximum makespan characterizes the production efficiency of the job-shop. The minimization of the maximum makespan needs to satisfy:

$$\min T_{\max} = \max_{1 \le i \le N} \sum_{j=1}^{N} \sum_{k=1}^{N_i} T_{ijk} \tag{13}$$

The total device load characterizes the working time of all devices. The minimization of the total device load needs to satisfy:

$$\min L_{TOTAL} = \sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{N_i} T_{ijk} \varphi_{ijk} \tag{14}$$

where, φ_{ijk} is a binary function about whether process P_{ik} is implemented on the j-th device E_j (if $\varphi_{ijk} = 1$, the process is implemented on that device; if $\varphi_{ijk} = 0$, the process is not implemented on that device).

The key device load determines which device is assigned to each process in the scheduling plan. The minimization of the key device load needs to satisfy:

$$\min L_j = \max_{1 \le i \le N} \sum_{i=1}^{N} \sum_{k=1}^{N_i} T_{ijk} \varphi_{ijk} \tag{15}$$

The dynamic job-shop scheduling is mainly subject to seven constraints: (1) the spatiotemporal exclusivity of devices, (2) the spatiotemporal exclusivity of processes, (3) the time continuity of processing, (4) the time limit of processing, (5) the sequence of processes, (6) the fairness of the priority of processes, (7) the start-up consistency of devices.

Let ST_{ik} be the start time of the k-th process P_{ik} of A_i. Since each device needs to execute more than one process, the time limit of processing can be defined as:

$$\begin{cases} ST_{ik} + \varphi_{ijk} \cdot T_{ijk} \le \sum_{j=1}^{M} \sum_{k=1}^{N_i} T_{ijk} \\ \sum_{j=1}^{M} \sum_{k=1}^{N_i} T_{ijk} \le T_{max} \end{cases} \tag{16}$$

The time continuity of processing can be defined as:

$$\sum_{j=1}^{M} \sum_{k=1}^{N_i} T_{ijk} \le ST_{i(k+1)} \tag{17}$$

The spatiotemporal exclusivity of processes can be defined as:

$$ST_{ik} + T_{ijk} \le ST_{i(k+1)} \tag{18}$$

Since each process of a workpiece must be assigned a device, the following constraint must be satisfied to find a device in the device set E_j for process P_{ik}:

$$\sum_{j=1}^{M} \varphi_{ijk} = 1 \tag{19}$$

4. Problem solving

For the multi-objective dynamic job-shop scheduling, the MOGA enjoys good optimization performance and model robustness, but faces several defects: the limited population size and the difficulty in saving the optimal solution. It is necessary to improve the algorithm in two aspects: reducing computing complexity and increasing the preservation probability of the optimal individuals.

To ensure the diversity of solutions, this paper replaces the calculation and selection of the crowded distance in the traditional MOGA with the selection of predefined reference points. Whereas three objectives have been chosen for the multi-objective dynamic job-shop scheduling, the reference points were defined on a three-dimensional hyperplane, and each objective was split into Q parts. Then, the number of reference points can be calculated by:

$$N_R = \binom{3 + Q - 1}{Q} \tag{20}$$

The coordinates of each point in the corresponding two-dimensional plane can be expressed as:

$$c_l = \left\{0, \frac{1}{Q}, \frac{2}{Q}, \dots, 1\right\} \tag{21}$$

The solution diversity of the target problem was maintained by the correlation between each reference point and each solution. The different scales of each objective function can be reflected by the reference points on the planes in the three-dimensional hyperplane. Therefore, the algorithm's preference for the scale of each objective function should be lowered through adaptive normalization.

Step 1: Regard the minimum of population K_t as the optimal point of the population. Set up the set of the optimal points $K = (K_{1-\min}, K_{2-\min}, \ldots, K_{D-\min})$ to transform the objective functions Eqs. 13-15 by:

$$F_i^*(x) = F_i(x) - K_{i-\min} \tag{22}$$

Step 2: Determine the extra points on the hyperplane by:

$$EP(x, \sigma) = \max_{i=1}^{3} \frac{F_i^*(x)}{\sigma_i}, \qquad x \in K_z \tag{23}$$

The i-th optimal point can be expressed as:

$$K_{i-\min} = c\text{: } \mathrm{argmin}_{c \in K_z} EP(x, \sigma^i), \sigma^i = (10^{-6}, \ldots, 10^{-6}), \qquad \sigma_j^i = 1 \tag{24}$$

Calculate the distance between the hyperplane and each coordinate axis, and perform adaptive normalization on each objective function by:

$$g_i^n = \frac{F_i^*(x)}{x_i - K_{i-\min}} = \frac{F_i(x) - K_{i-\min}}{x_i - K_{i-\min}}, \qquad i = 1,2,3 \tag{25}$$

Step 3: Solve the connected reference line of the first V non-dominated optimal layers. Specifically, calculate the vertical distance on the hyperplane for the reference line ς between the origin and reference point corresponding to each individual K by:

$$D^{\perp}(K, \varsigma) = \|(K - \varsigma^T K \varsigma)/\|\varsigma\|^2\| \tag{26}$$

Then, define the reference point corresponding to the shortest distance as the connected reference point, and the corresponding connected reference line can represent the correlation between the connected reference point and each solution.

Fig. 6 explains the workflow of the proposed algorithm for solving dynamic JSP.

Step 1: Initialize the objective functions, coding method, and parameters.

Step 2: Generate a fixed number of predefined reference points, according to the number of optimization objectives of the multi-objective dynamic job-shop scheduling, as well as the number of equal divisions of each objective.

Step 3: Make the initial number of iterations zero, generate a population $K_t$of the size D that meets the seven constraints of dynamic job-shop scheduling, and perform fitness calculation

Step 4: Generate new individuals through crossover, and obtain a new population K_t' through mutation.

Step 5: Perform fitness calculation for the new population K_t, merge the new and old populations, and conduct rapid dominated and non-dominated sorting of individuals, and obtaining the non-dominated optimal layers. By assigning a shared virtual fitness to all non-dominated individuals, obtain the non-dominated optimal layers, such as rank1, rank, rank3, etc.

Step 6: Perform adaptive normalization of individuals in the next-generation population, compare the vertical distances of all reference lines of all individuals on the hyperplane, obtain the set of reference points connected with all individuals with the shortest distance, and compute the niche of each reference point. The preservation of the niche can be realized through the following steps:

- Let $\Omega_{min} = \{z\text{:}argmin_z \upsilon_z\}$ be the set of reference points for the minimum niche.

- Randomly choose reference points from $\Omega_{\min}$, which contains multiple reference points, and assemble them into the set Ψ_z of connected individuals on the V-th layer.

  If Ψ_z is empty, there is no individual on the V-th layer connected with the selected reference point; thus, remove this reference point.

  If Ψ_z is not empty, and if υ_z equals zero, take the individual with the shortest vertical distance as the optimal individual, pass it down to the next generation, and make $\upsilon_z = \upsilon_z + 1$; if υ_z is greater than 1, randomly choose an individual from the V-th layer, pass it down to the next generation, and make $\upsilon_z = \upsilon_z + 1$.

Step 7: After niche preservation, judge if the size of the next-generation population reaches the preset value. If yes, it means the iterations have completed. Then, judge if the number of iterations meets the preset maximum value. If yes, terminate the iteration, and output the result; otherwise, make $t = t + 1$, and continue with the iterative process.

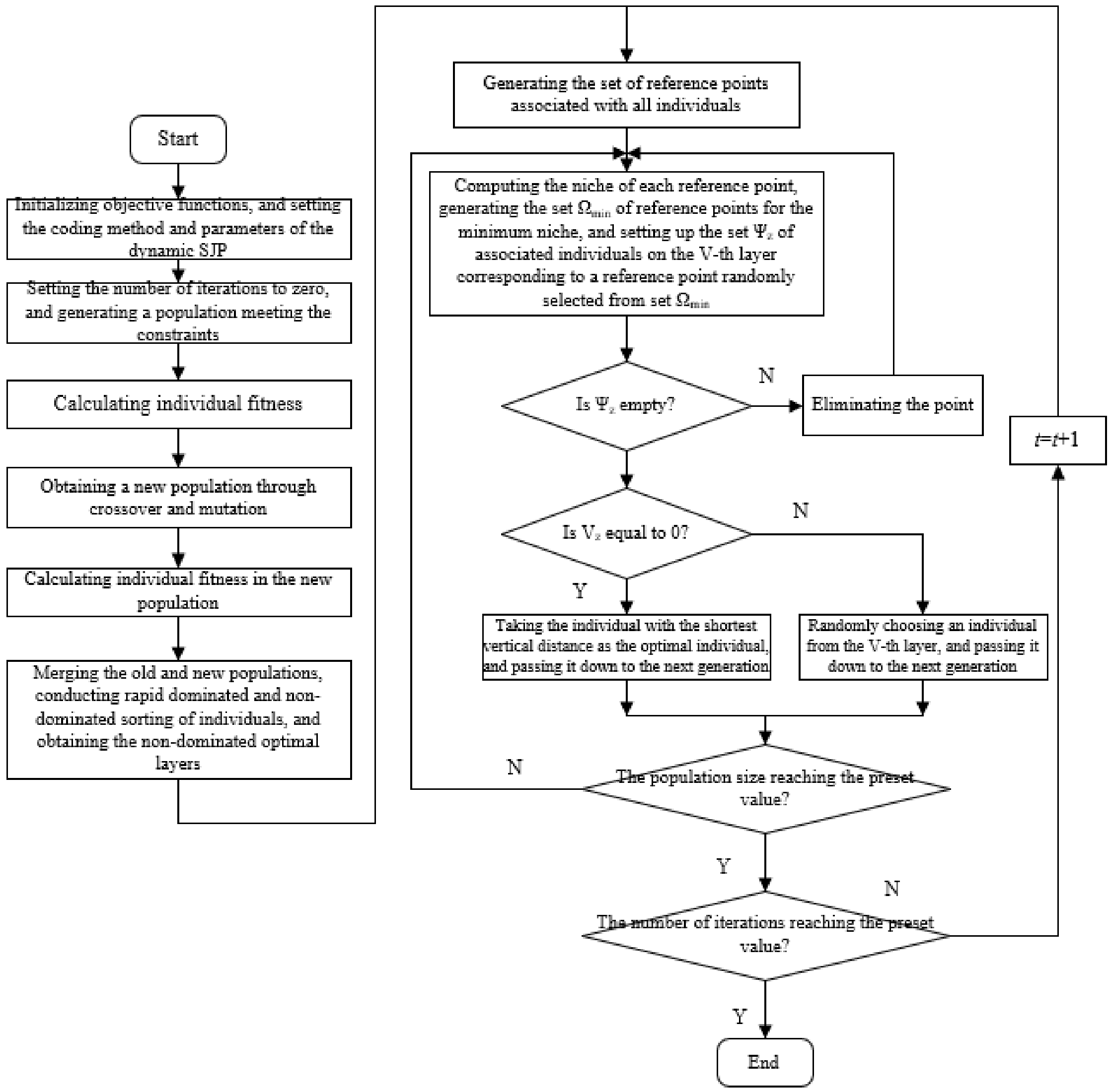

Fig. 6 Workflow of solving dynamic JSP based on MOGA

5. Experiments and results analysis

The hyperparameter setting directly determines the accuracy of the proposed LSTM-based data prediction model for dynamic job-shop scheduling. In this paper, tanh is selected as the activation function of the network, mean squared error (MSE) is taken as the objective function, ADAM is chosen to improve the parameters, and the batch size is set to 30.

The degree of feature extraction from dynamic job-shop scheduling data depends on the hidden layer(s). Table 1 shows the prediction results at different number of hidden layers. Obviously, the MSE, MAE, and MAPE of our model were minimized, when there were five hidden layers. Table 2 presents the prediction results at different number of nodes in the hidden layer. It can be seen that, when there were 25 hidden layer nodes, the MAE and MAPE were minimized, and the MSE was relatively small. Since a small loss means highly accurate prediction, the number of hidden layers and the number of hidden layer nodes were set to 5 and 25, respectively.

Table 1 Prediction results at different number of hidden layers

Number of layers	1	2	3	4	5	6	7	8	9
MSE	23.69	22.44	21.61	20.91	19.18	20.93	21.33	22.64	23.11
MAE	16.71	15.28	14.57	13.99	13.18	13.37	14.29	15.23	16.50
MAPE	8.93	8.54	8.57	7.28	6.84	7.03	7.53	8.27	8.49

Table 2 Prediction results at different number of hidden layer nodes

Number of nodes	5	10	15	20	25	30	35	40
MSE	22.45	21.19	20.64	20.84	20.97	21.09	21.91	22.10
MAE	16.74	15.36	15.49	14.73	14.26	14.58	15.53	15.67
MAPE	7.86	7.37	7.49	7.26	6.81	7.15	7.36	7.89

To verify its effectiveness, the proposed deep LSTM for data prediction of dynamic job-shop scheduling was compared with support vector machine (SVM) through experiments. A total of 7,500 pieces of data were selected to train the model, and 2,500 sets of data to test the model. Tables 3-5 present the test results on any five sets of test data.

Table 3 Test data of objective functions

Serial number	Input data			
	Maximum makespan	Processing cost	Key device load	Total device load
1	51	15.217	77	184
2	62	11.463	89	169
3	55	13.503	93	215
4	64	15.227	84	210
5	59	9.803	76	175

Table 4 Test data of SVM

Serial number	Output data			
	Maximum makespan	Processing cost	Key device load	Total device load
1	48	14.863	83	210
2	68	11.980	80	184
3	53	14.254	91	201
4	60	14.739	98	231
5	64	11.004	84	168

Table 5 Test data of LSTM

Serial number	Output data			
	Maximum makespan	Processing cost	Key device load	Total device load
1	50	14.291	74	192
2	59	10.649	95	173
3	54	15.210	92	206
4	62	15.972	79	199
5	60	9.599	82	167

Based on the test results, this paper selects five indices to measure the performance of each prediction model: accuracy, precision, recall, comprehensive evaluation index (CEI), and area under the curve (ACU). The SVM is a supervised learning model. It is often adopted to analyze data, predict classes, and regress data. Table 6 compares the prediction performance of SVM and LSTM. It can be seen that, when only the processes in Fig. 5 were considered (e.g., casting, forging, cold stamping, welding, metal cutting, heat treatment, assembly, body installation, painting, testing, finished product packaging), the proposed model outperformed the SVM, as it achieved the higher values of all metrics.

Fig. 7 shows that the ROC curve of SVM remained below that of LSTM. This further confirms that our data prediction model for dynamic job-shop scheduling is better than the other models, and is highly feasible.

Normally, multi-objective planning problems can be modeled into the search for Pareto optimal solutions. Compared with traditional genetic algorithm, adaptive genetic algorithm boasts the ability to solve multiple objectives, strong robustness, and excellence in optimization. The adaptive genetic algorithm II is improved from NSGA, by optimizing the elite strategy for retaining the optimal solutions. On this basis, the adaptive genetic algorithm III is derived by replacing the crowded distance. The two algorithms are widely used in many fields. To verify the superiority of our algorithm, this paper sets up a dynamic job-shop scheduling model with three objective functions: minimal maximum makespan, minimal total device load, and minimal key device load. Then, the model was solved by the proposed algorithm, adaptive genetic algorithm II, and adaptive genetic algorithm III. Table 7 lists the maximum, mean, and minimum of the objective functions obtained by the three algorithms. Fig. 8 displays the solution sets of the three algorithms in a three-dimensional space. The mean Euclidean distance from each reference point to the nearest solution was computed to measure the performance of the above three methods. The algorithm with the smallest inverted generational distance has the best performance. It can be seen that our algorithm achieved comparable results as adaptive genetic algorithms II and III in key device load, while significantly outshined the two algorithms in maximum makespan and total device load.

Table 6 Prediction performance of SVM and LSTM

Prediction model	Accuracy	Precision	Recall	CEI	ACU
SVM	92,16	90.62	95.72	96.33	0.875
LSTM	94.37	95.11	96.21	96.78	0.898

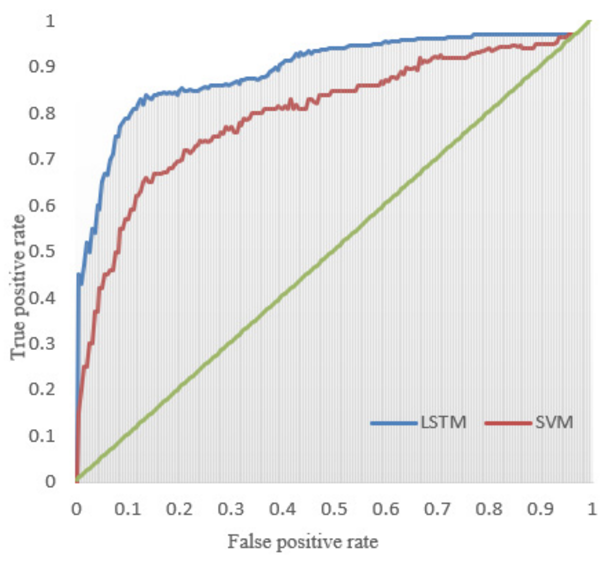

Fig. 7 ROC curves of SVM and LSTM

Table 7 Solving results of different algorithms

Objectives		Adaptive genetic algorithm II	Adaptive genetic algorithm III	Our algorithm
	Max	64.34	62.15	60.75
Maximum makespan	Mean	53.18	54.11	53.77
	Min	49.79	50.17	52.15
	Max	98.13	92,75	90.22
Key device load	Mean	87.84	86.14	86.05
	Min	69.47	71.94	78.25
	Max	247.49	231.85	210.05
Total device load	Mean	181.64	184.23	183.55
	Min	167.21	170.51	170.26

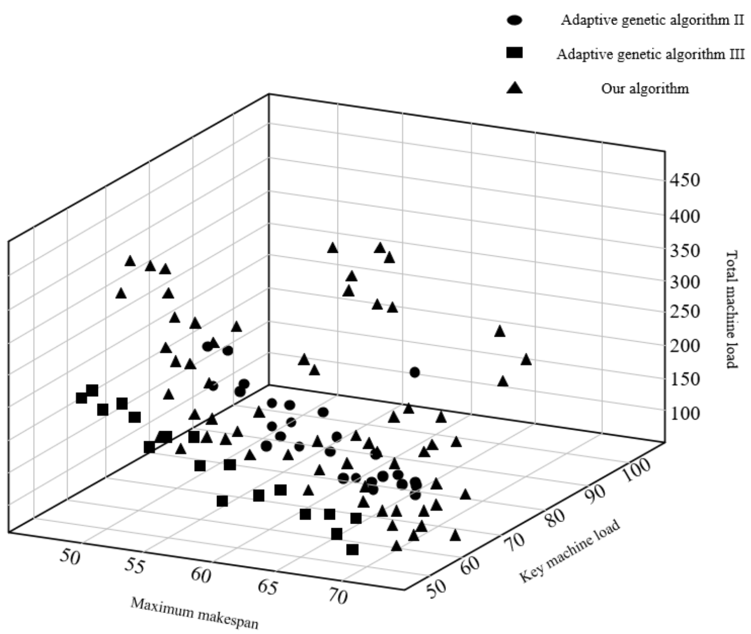

Fig. 8 Solving results of different algorithms for dynamic JSP

6. Conclusion

This paper mainly proposes a dynamic job-shop scheduling model based on DL. Firstly, a data prediction model was innovatively constructed based on LSTM. Then, the Dropout technology and ADAM were introduced to enhance the generalization ability and prediction effect. To evaluate the prediction performance of the model, five metrics were selected, including accuracy, precision, recall, CEI, and ACU. The experimental results show that our model outperformed the SVM. Next, the three objective functions, namely, maximum makespan, total device load, and key device load, were optimized, completing the description of dynamic JSP. Finally, the MOGA was improved innovatively to solve the multi-objective dynamic JSP. From the experimental results, it is inferred that our algorithm achieved comparable results as adaptive genetic algorithms II and III in key device load, while significantly outshined the two algorithms in maximum makespan and total device load.

In future, the research contents will be deepened in the following aspects: the strategy for maintaining population diversity will be further improved, shedding light on combinatory optimization. Better evaluation indices will be found to measure the convergence of the algorithm. The test set will be expanded to reflect the actual production situation of flexible WSP.

Acknowledgement

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Multi-objective automated guided vehicle scheduling based on MapReduce framework

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A B S T R A C T

During material handling processes, automated guided vehicles (AGVs) pose a path conflict problem. To solve this problem, we proposed a multi-objective scheduling model based on total driving distance and waiting time, and used the A* path planning algorithm to search the shortest path of AGV. By using a speed control strategy, we were able to detect the overlap path and the conflict time. Additionally, we adopted an efficient MapReduce framework to improve the speed control strategy execution efficiency. At last, a material handling system of smart electrical connectors workshop was discussed to verify the scheduling model and the speed control strategy combined with the MapReduce framework is feasible and effective to reduce the AGV path conflict probability. The material handling system could be applied in workshop to replace manual handling and to improve production efficiency.

A R T I C L E I N F O

Keywords:
Automated-guided vehicle(AGV);
Scheduling;
AGV scheduling;
MapReduce;
Path planning;
A* search algorithm

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1. Introduction

Automated guided vehicles (AGVs) are automated intelligent unmanned vehicles that rely on electromagnetic, laser, and visual navigation equipment to complete a series of transportation and assembly tasks under the control of a scheduling system along a guided path between workstations. In the actual production environment, through cooperative work, multiple AGVs are able to quickly and efficiently complete tasks, such as material handling, warehousing, and transportation. The scheduling system of the AGVs should pursue the global optimal solution, and determine a reasonable allocation plan to achieve the best match between the tasks and the AGVs.

As a key part of future automated logistics, AGV systems have broad development prospects, and the research of scheduling technology, which is the core of the AGV automatic transportation system, should be highlighted. As a concurrent system, simultaneous operation of multiple AGVs inevitably causes conflicts and deadlocks, which severely negatively affects the efficiency and reliability of the system operation. The traditional control system generally adopts a centralized scheduling strategy, in which a path planning algorithm and the task scheduling process of multiple AGVs are carried out by a central controller. Thus, the increasing number of AGVs will make the system structure and path planning algorithm exceedingly intricate. In terms of AGV system scheduling, Fazlollahtabar *et al*. provided an overview of AGV scheduling and path planning [1, 2] and compared relevant methods. Common algorithms include the Dijkstra algorithm [3, 4], A*algorithm [5-10], ant colony algorithm [11-13], and fuzzy and path planning algorithm [14-17]. Liu *et al*. proposed a scheduling algorithm [18] that considered the process route based on a genetic algorithm. Li *et al*. considered the priority of various tasks to minimize the total path length [19, 20]. They studied the application of queuing theory in AGV scheduling with the storage and transportation system as the research object. Zheng *et al*. studied AGV scheduling technology based on an endocrine hormone regulation mechanism [21, 22]. Most scheduling strategies, however, are based on a *push strategy* and cannot accommodate the needs of production models.

From the perspective of fulfilling the actual application requirements of production systems, this study focused on AGV scheduling system modeling and AGV path planning to research a multi-objective compound task scheduling model and AGV path search algorithm. We adapted the task handling requirements in complex production scenarios, thereby raising the overall operating efficiency of the system.

2. Proposed multi-objective compound task scheduling model

2.1 Multi-objective scheduling model

The material handling system of workshop is shown in the Fig. 1. *A, B*, and *C* are the three loading and unloading manipulators in the production workshop; *a, b,* and *c* are shelving areas in the warehouse, where *a* is the shelf area of the incoming materials, and *b* and *c* are the shelf areas of the outgoing materials. In the storage task, the AGV is required to load the pallet from the designated manipulator and carry it to the designated material storage area. In the outgoing task, the AGV is required to load the pallet from the designated outbound material area and carry it to the designated manipulator buffer area. The *A, B,* and *C* manipulators handle the task of loading and unloading materials, but only the *A* manipulator handles the task of loading and unloading.

Multi-AGV scheduling systems are established on the basis of indexes, including waiting time, queue length, system throughput, running distance, and vehicle utilization percentage. Considering that the efficiency of the handling task is reflected primarily in vehicle running distance, task waiting time, and task priority in actual production, we proposed a multi-AGV task scheduling model based on total driving distance, waiting time, and the priorities of handling tasks. The objective function is shown as follows:

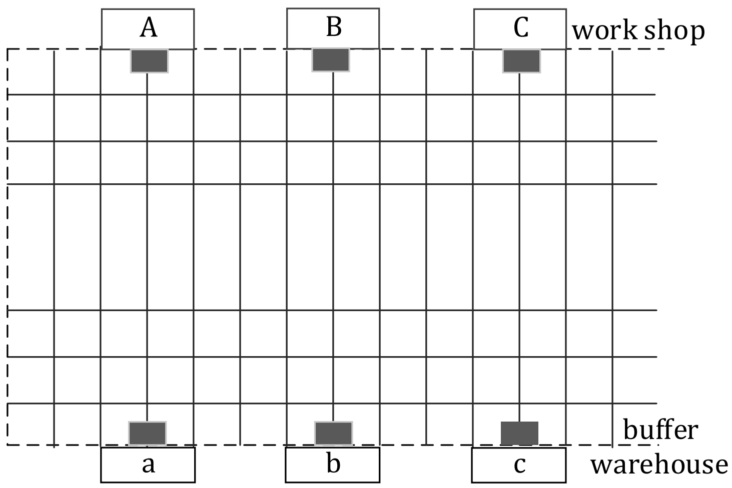

Fig. 1 The layout of the material handling system of workshop

$$\begin{cases} F = min \sum_{i=1}^{m} \sum_{j=1}^{k} (u_1 t_i + u_2 p_i + u_3) x_{ij} d_{xj} \\ s.t. \sum_{i=1}^{m} x_{ij} = 1,\ j = 1,2,\cdots,k \\ \sum_{j=1}^{k} x_{ij} = 1, i = 1,2,\cdots,m \\ x_{ij} = \{0,1\} \\ i = \{1,2,\cdots,m\}, j = \{1,2,\cdots,k\} \end{cases} \tag{1}$$

Where m is the current number of tasks; k is the number of currently available AGV vehicles; $x_{ij} = 1$ indicates that the i-th task is executed by the j-th AGV, or $x_{ij} = 0$; d_{ij} indicates the path length of the i-th task being executed by the j-th AGV; t_j is the waiting time of the i-th task at the current time; p_j is the priority of the i-th task at the current time, and u_1, u_2, u_3 is the weight coefficient.

Without a clear allocation theory for the weight coefficient, it is difficult for the current composite scheduling model to quantitatively analyze whether the weighting coefficient distribution method is reasonable. Therefore, we determined the weight coefficient according to the empirical method and dynamically adjusted the weight ratio according to the system performance.

2.2 Description of path feature

The three usual types of conflicts in the AGV path planning [23] are position conflict, opposite conflict, and same direction conflict. A position conflict occurs when multiple AGVs arrive at the same location at the same time. An opposite conflicts occurs when two AGVs meet in a path that is available for only one AGV without giving way to the other. A same direction conflict occurs when multiple AGVs run in a direction on the same path, and the latter AGV operating at a higher speed collides with the AGV ahead. Therefore, the setting of path should be restricted to avoid these three conflicts. To improve the adaptability and reliability of the AGV system, the AGV path characteristics are described as follows:

(1) Each AGV can receive only one task once, which can be changed before the AGV enters the pickup section. After it, the task cannot be changed, and the current task must be completed before accepting the next.
(2) The driving speed of each AGV is set the same when the linear and turning speeds alternate according to the actual running conditions.
(3) The deceleration and acceleration of each AGV are set the same at approaching or leaving the target point.
(4) Each section is a one-way path, with the fixed driving direction.
(5) Multiple AGVs are allowed to run simultaneously on each section.
(6) A safe distance is set between vehicles to avoid rear-end collision.
(7) A sufficient driving distance is set between any two parallel road sections to avoid road scraping.
(8) Each path intersection zone is a bicycle-only area, which allows one AGV at one time.

2.3 Path planning algorithm

To solve the shortest path when the map environment is known, scholars globally have studied many algorithms, including the genetic algorithm, neural network algorithm, Dijkstra's algorithm, and A* algorithm. The genetic algorithm randomly selects the initial population by coding through a simulation of the genetic and variability of chromosomes to calculate the adaptive function and the selection rate. Thus, the algorithm can simulate the crossover and mutation behavior to determine whether the next generation satisfies the demand. The solution to the optimal path requires multiple iterations and requires computational intricacy. The Dijkstra's algorithm is characterized by adopting a step-by-step extended search strategy similar to the equipotential line and searches only partially connected nodes. As a heuristic search algorithm, A* algorithm adds some qualification, which can effectively discard some path points and strengthen the search efficiency. The A* algorithm combines the ideas of best-first search and Dijkstra's algorithm, and adopts heuristic search to ensure the optimal path. The A* algorithm uses an evaluation function to determine the search direction and expands from the starting point to the surrounding area. A surrogate value of each surrounding node is calculated by the evaluation function. The minimum cost node is selected as the next expansion node, and the process is repeated. In the process of searching, every node on the path has the latest cost.

To comprehensively consider the path search efficiency, we selected A* to search for the shortest path. The A* algorithm can be described by Eq. 2:

$$f(n) = g(n) + h(n) \tag{2}$$

Where, $f(n)$ is an estimated distance from the starting point to the target point though the path point n; $g(n)$ is the actual distance from the starting point to the path point n; $h(n)$ is the distance estimation function from the path point n to the target point. The Euclidean distance from the path point n to the target point is selected as an estimation function, that is, $h(n) = \sqrt{(x_d - x_n) + (y_d - y_n)}$, where x_d, y_d are the coordinates of the target point and x_d, y_d are the coordinates of the path point n. The algorithm process is shown in Fig. 2.

As shown in Fig. 2, we set the AGV starting position point as the starting point k, searched for the path point connected to the starting point k, and calculated the distance between k and all the path points. We selected the path point with the smallest distance as the new search starting point and continued this process until the target point was found.

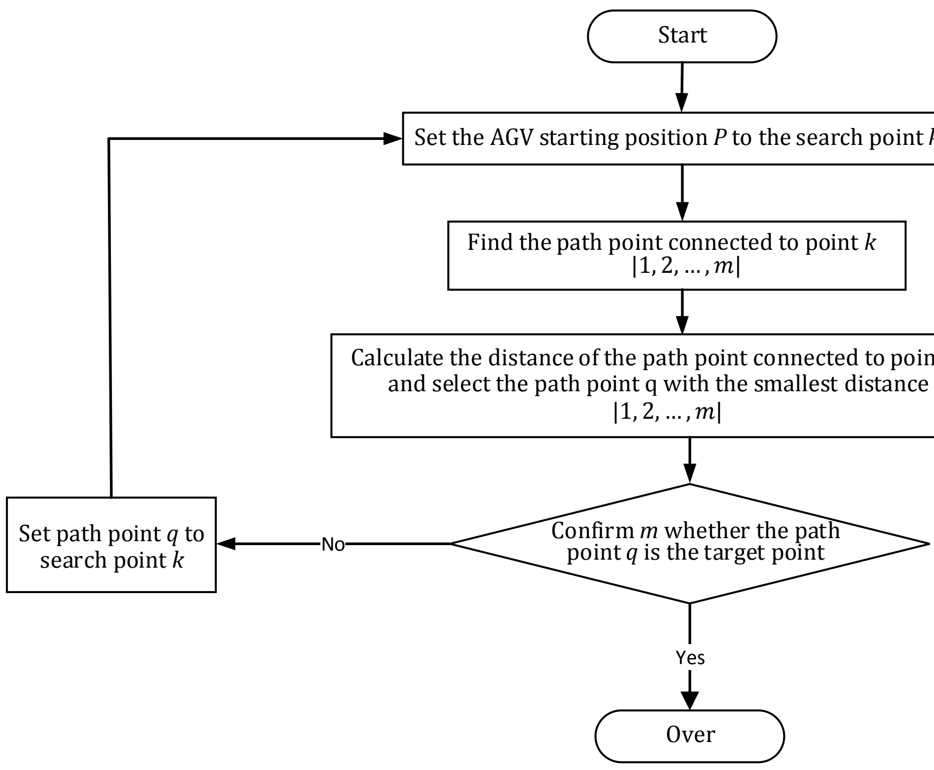

Fig. 2 The flow chart of the A* algorithm

2.4 Path conflict detection strategy

According to the materials handling system as shown in the Fig. 1, we used the graph theory to realize the mathematical representation of the map. The graph is denoted as $G = (N, W)$, where N is a set of nodes, W is a set of edges. $W_{k(i,j)} = (n_i, n_j)$ represents the edge of path k from node i to node j, where $i \neq j$ and $i, j \neq 1,2,\cdots,n$, and n is the number of nodes. The notation used in this section can be summarized as shown in Table 1.

Table 1 Key notations

Symbols	Description
L	The length of AGV
L_s	The safe length of two AGVs on the same path
P	The set of all paths
k	The index of paths, $k = 1, 2, 3, \ldots$
P_k	Path number k
K	The set of index of paths, $k \in K$
AGV_{km}	AGV number m of P_k
D_k	The distance of path k, $k \in K$
N_k	The set of points of path k, $k \in K$
n_{ki}	The point number i of path k, $k \in K$
$C_{(k_a,k_b)}$	The set of conflict points of path k_a, k_b , $k_a \in K$, $k_b \in K$
C_{kr}	The conflict point number i of path k, $k \in K$
s	The start position of path k, $k \in K$
e	The end position of path k, $k \in K$
t_{kms}	The start time of AGV m of path k, $k \in K$
t_{kmc_r}	The spending time that AGV m arrival to the conflicts node r of path k, $k \in K$
t_{kme}	The end time of AGV m of path k, $k \in K$
tc_k	The set of the time that AGVs arrival to the conflict nodes of path k, $k \in K$
TC	The set of the time that AGVs arrival to the conflict nodes
T	The total time of all conflict time

We identified an AGV path conflict if the two AGVs arrived at the same node at the same time. One should run away from the other AGV to avoid the path conflicts. Therefore, we gave the minimum safety length L_s of the two AGVs on the same path.

To detect AGV path conflicts, we considered both the path overlap and the time conflicts that pass the node. Between the conflict nodes, there were non-conflict paths in which the AGV normally could pass. The speed of AGV was v_0. Eq. 3 calculates the conflict detection of the path node. Eq. 4 calculates the conflict detection of the pass time and L/v_0 represents the total time from arrival to pass the conflict node. To guarantee the drive safety of the two AGVs, the absolute value of the time difference between the two AGVs arrival to the conflict path should be no less than $(L + L_s)/v_0$, or else we call it AGV conflicts happen.

$$C(k_1, k_{11}) = N_K \cap N_K \tag{3}$$

$$\mathrm{TC} = |\mathrm{tc_k} - \mathrm{tc_k}| < (\mathrm{L} + \mathrm{L_s})/\mathrm{v_0} \tag{4}$$

When we detected the AGV path conflict, the priority of the AGVs should be sequenced. The lower priority AGV should wait until the higher priority AGV passed the conflict path for the multiple AGVs approaching the conflict path. The longer the time of arrival at the conflict section, the later the arrival would be; therefore, priority was lower, and the AGV that arrived first would move forward.

The solution for path conflicts is the speed control strategy. For the speed control strategy, we kept the higher priority AGV drive speed uniform, but changed the lower priority AGV drive speed. We gave acceleration a for the speed change. In Eq. 5, l_s represents the path length of AGV decelerating from v_0 to v_1 or accelerating from v_1 to v_0. Eq. 6 represents the AGV decelerates to v_1, and then AGV passes through the conflict node at constant speed v_1. Eq. 8 and Eq. 9 represent the spending time before the AGV arrival to the conflicts node the speed change. Eq. 10 and Eq. 11 represent the spending time that AGV arrival to the conflicts node 1, 2, and r accordingly. Eq. 12 represents the total time for the AGVs arrival to the terminal.

$$l_s = (v_0^2 - v_1^2)/2a \tag{5}$$

$$(L + L_s)/v_0 = (v_0 - v_1)/a + (L + L_s)/v_1 \tag{6}$$

$$t_1 = (L + L_s)/v_0 \tag{7}$$

$$t_2 = (v_0 - v_1)/a \tag{8}$$

$$t_{k1mc1} = t_{kms} + t_1 + \left(W_{k(s,uk1)} - L_S\right)/v_0 \tag{9}$$

$$t_{k1mc2} = t_{k1m1} + \left(W_{k1(s,uk1)} - L_S\right)/v_0 + t_2 \tag{10}$$

$$t_{k1mc2} = t_{k1m1} + \sum_{i=2}^{ukr}\sum_{j=2}^{ukr} W_{k1(i,j)} \Big/ v_0 = t_{k1mc2} + \sum_{i=2}^{ukr}\sum_{j=2}^{ukr} \left(n_{k1i}, n_{k1j}\right) \Big/ v_0 \tag{11}$$

$$min\, T_{k1m} = t_{k1m1} - (L_s - l_S)/v_0 + t_1 + t_2 \tag{12}$$

2.5 Efficient MapReduce framework

MapReduce [24, 25] is a parallel computing framework for cluster systems. Phoenix++ [26] is a C++ programming implementation of the MapReduce framework based on shared memory, which can be used to program multi-core chips and shared memory multiprocessors. MapReduce framework optimization provides the opportunity to reuse hash table storage space between multiple Map tasks and reuse the hash table between multiple Reduce tasks. Accordingly, we designed a high-efficiency reusable hash table (HRHT). Considering that the unordered map used by Phoenix in the Reduce stage used a linked list to store data, we had to apply space for each pair of *keys/values* to create a node, which caused a large number of memory applications. As a result, the HRHT designed in this study eliminated the use of linked lists. Fig. 3 displays the data structure and data access process of HRHT, which improved the *unordered_map* as follows:

Step 1: A valid flag added to each bucket indicated that the data in the corresponding bucket were invalid, and the bucket could be used to store new data. The data in the corresponding bucket were valid, that is, the current bucket was already occupied. When the hash table needed to be reused, it had to reset all valid flags to 0, and thus invalidated all the data in the bucket. The HRHT could be quickly reset by the valid flag to ensure high efficiency reuse of the hash table.

Step 2: The linked list was no longer used, and the *key/value* pairs were saved directly to buckets. When there were data to be added, they were mapped to a position in the buckets according to the key. We then checked the buckets backward from the position, found a location with a valid flag of 0 from the buckets, and then saved the new data. Thus, we no longer had to apply for space temporarily.

In this study, we introduced HRHT into the design of the hash container and designed it as an HRHT-based hash container. Then we replaced the unordered map of Reduce stage with HRHT to avoid the application of a large number of small blocks of memory. In addition, HRHT also guaranteed that the bucket size was a power of 2 when being designed. After the hash value was calculated by *Hash*(), when positioned in the bucket, we used (*hash_value&*(*buckets_size-1*)) to replace the previous modulo calculation (*hash_value%buckets_size*) and thus improved retrieval efficiency.

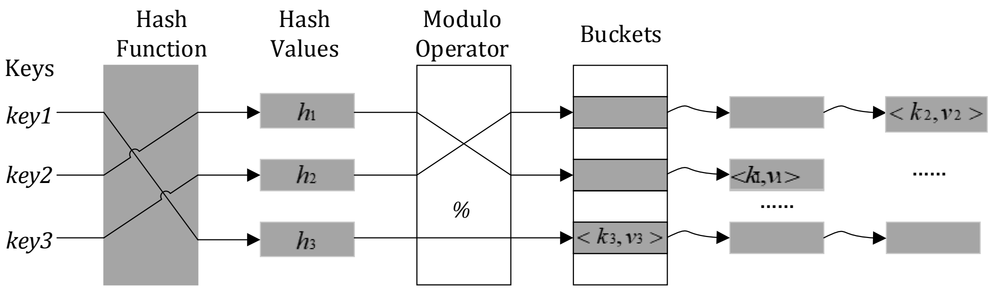

Fig. 3 The data structure of HRHT

3. Experimental analysis: Results and discussion

In this study, we took the logistics of an electrical connector workshop as the research background. A, B, and C were the three loading and unloading manipulators in the production workshop and a, b, and c where the shelving areas in the warehouse. Symbol a represents is the shelf area of incoming materials, b and c are the shelf areas of outgoing materials. In the storage task, the AGV was required to load the pallet from the designated manipulator and had to carry it to the designated material storage area. In the outgoing task, the AGV was required to load the pallet from the designated outbound material area and carry it to the designated manipulator buffer area. The A, B, and C manipulators handled the task of loading and unloading materials, but only the A manipulator handled the task of loading and unloading.

In this analysis, the experimental system is based on Intel Xeon E5645 platform (6 cores per CPU, 12 CPUs in total), which can be used to run MapReduce framework Phoenix++, and is used CentOS 6.5 as the operating system and GCC 4.7 as the compiler. We set work for three AGVs, and then set basic parameters: $L = 1.2$ m, $L_s = 1$ m, $v_0 = 1.2$ m/s, $v_1 = 0.8$ m/s, and $a = 0.4$ m/s^2. We used the A* algorithm to plan the AGV operation path. The path of the AGV is shown in Figure 4, and the overlap of each path is given in Table 2.

We compared the impact of speed control strategy combined with efficient MapReduce framework on the AGV total travel time. Compared with the normal arrival time, the 0 time difference indicated that the AGV driving state in the path remained unchanged; a positive time difference indicated that the AGV waited in the path. As shown in Fig. 5 and Fig. 6, the efficient MapReduce framework improved the execution efficiency of the speed control strategy and shortened the spending time of the entire loading and unloading process.

With the increase of the number of tasks and AGVs, the possibility of conflict path segments between different paths increased, which led to an increase in the probability of conflict between AGVs. We predicted the probability of conflict between AGVs, as shown in Fig. 7. It can be seen that the efficient MapReduce framework improved the execution efficiency of the algorithm and reduced the probability of conflict between AGVs.

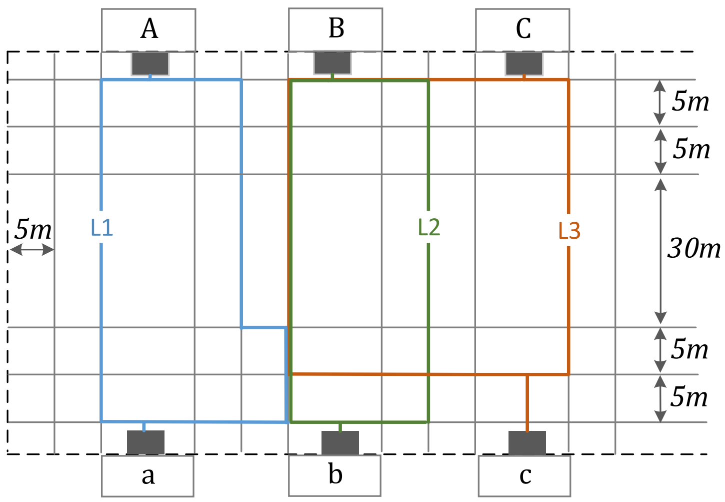

Fig. 4 The map of AGVs

Table 2 Overlapping paths

No.	Path number	Path length	Number of overlapping paths
1	L1	140 m	L2, L3
2	L2	130 m	L1, L3
3	L3	155 m	L1, L2

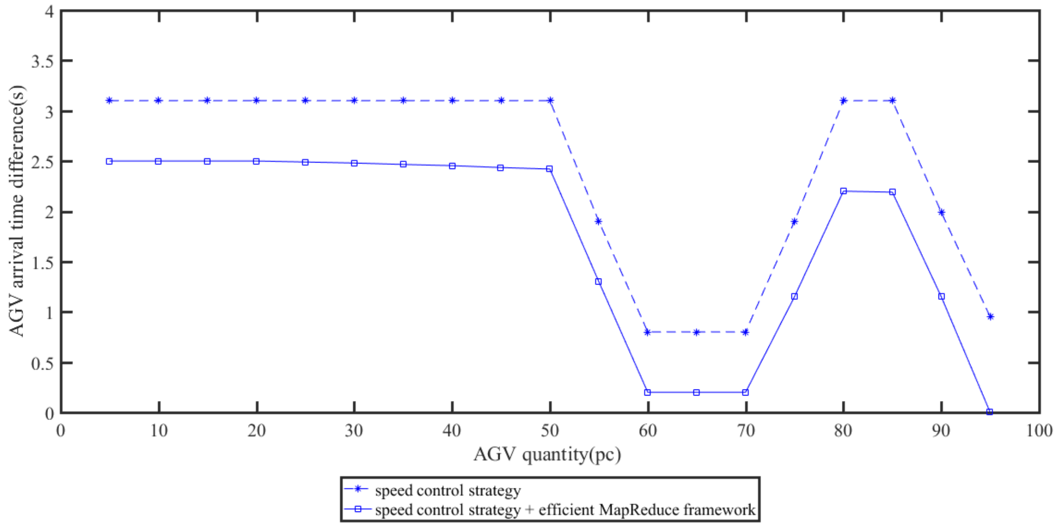

Fig. 5 Changes in the time of the AGV arrival time

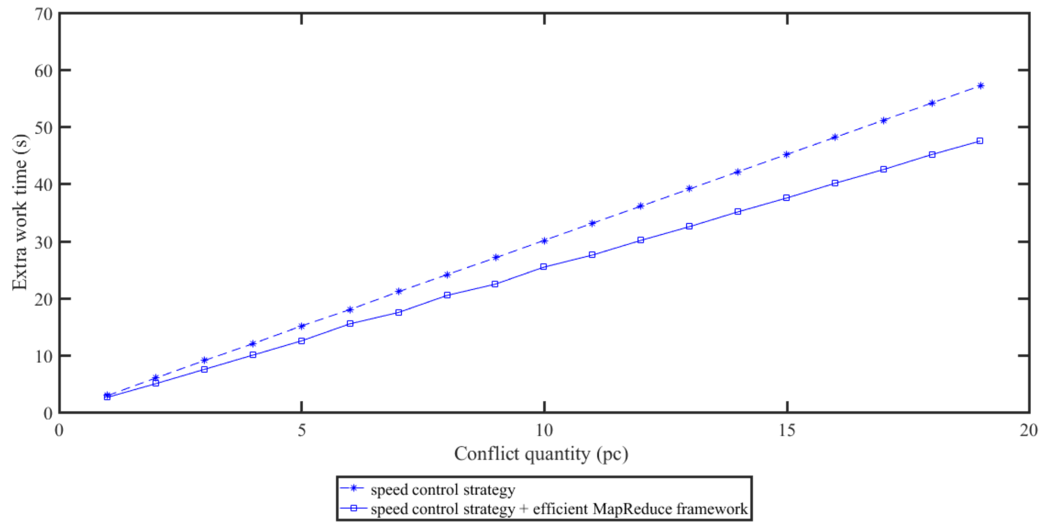

Fig. 6 The impact of speed control strategy combined with efficient MapReduce framework

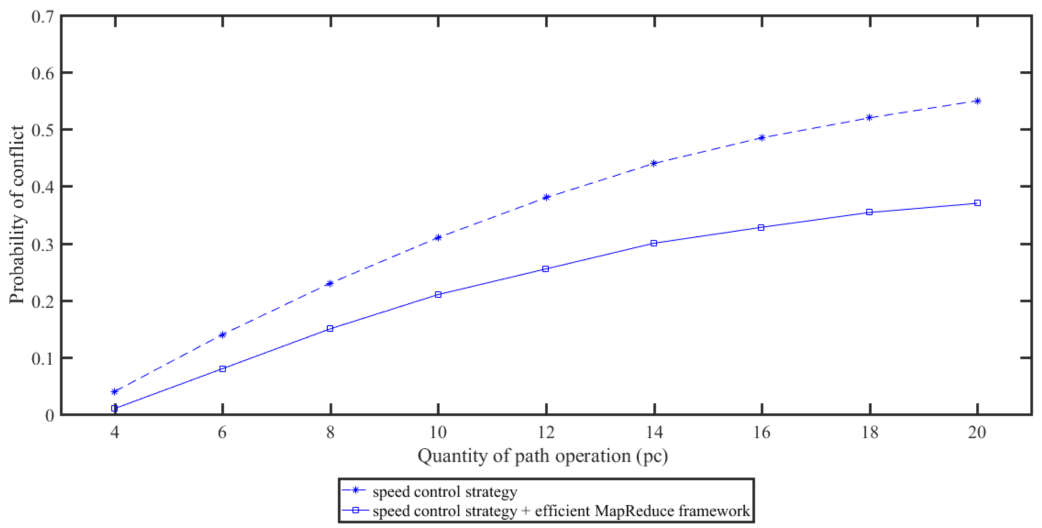

Fig. 7 The prediction of conflict between AGVs

4. Conclusion

In this paper, a multi-objective scheduling model is proposed based on total driving distance and waiting time, the A* algorithm is selected to search the shortest path of AGVs , the speed control strategy is proposed to detect path conflict without changing the driving path and task scheduling, the MapReduce framework is adopted to improve the speed control strategy execution efficiency. The experiment is proven to the scheduling model and the speed control strategy combined with the MapReduce framework is feasible and effective to reduce the probability of conflict in material handling process of AGVs.

In the future work, more researches should be carried on dynamic scheduling model of multi-AGV to solve the path conflict occurred in large-scale material handling process of AGVs.

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A conceptual model for measuring the competency level of Small and Medium-sized Enterprises (SMEs)

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A B S T R A C T

Small and Medium-Sized Enterprises (SMEs) are of major importance to developing countries. SMEs are the main drivers to strengthen society in sustaining economic growth and development. Governments provide various support programs to improve their industrial power and to increase the number of enterprises in the market. The enterprises must be assessed and suitable funds should be provided to those in need, to achieve an effective support program in the most efficient way.This requires implementing an assessment methodology based on a predefined set of scientific criteria. The current literature is comprehensive enough to assess the healthiness of the enterprises concerning strategic, technologic, financial as well as intellectual competencies but on the other hand, it lacks of an assessment model. This study aims to introduce a general framework for sustaining an effective assessment methodology for SMEs to eliminate this gap. The proposed model measures five different types of competencies such as Technological Competency, Strategic Competency, Financial Competency, Intellectual Competency, R&D and Innovation Competency. These competencies are to put forth the conditions in which the enterprises are running accurately. A real-life case study is conducted to ensure the baseline of the model to be implemented. The governmental organizations may utilize the model for sustaining their support role effectively to SMEs.

A R T I C L E I N F O

Keywords:
Small and medium-sized enterprises (SMEs);
Competency assessment;
Technological competency;
Strategic competency;
Financial competency;
Intellectual competency;
R&D and innovation competency;
Smart manufacturing;
Industry 4.0

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1. Introduction

SMEs are considered to be the foundation pillar of a country's economic and social development. SMEs have a series of positive characteristic such as, their ability to adapt quickly in changing markets, flexibility in their production structures, their contribution to balanced growth between regions and their influence on the reduction of unemployment and creation of new areas of employment. Since most of the SMEs try to survive with a limited capital and to do business mainly by experienced manual labor, they always need state-support to improve their infra-structure especially at the age of Industry 4.0. The era of digital transformation offers various opportunities for enterprises to sustain competitive advantage. New business models enabled enterprises to grow their market share. A comprehensive assessment of the existing capabilities and competencies are required, in order to achieve better utilization of technology for the sake of digitization. While considering quality, cost, efficiency and environment, the enterprises should also perform the necessities of transition to Industry 4.0. Being able to utilize the technology especially digital operations and methods like autonomous systems would improve the capability of the respective SME to respond to the market requirement in an early and effective manner. This would definitely contribute to the competency of the enterprise ensuring sustainable competitiveness. Therefore, digital transformation and intelligent (smart) devices are considered to be one of the core elements of respective (technological) competency. The effects of smart and intelligent manufacturing to the competency level of the enterprise are explained below.

SMEs may increase the economic situation through producing products and services as in the same way large companies operate. They have to be supported to both improve both quality and variety of products semi-finished products the produce. In this way, SMEs may contribute to the whole economy as well as related innovation and creativity. It should be kept in mind that these enterprises, whose goal is to stay on their feet and grow in the cutthroat competition of today's business world, are the barometer of economic buoyancy. Economic buoyancy needs to create a competitive environment by growing as many SMEs as possible and by challenging the birth of lots of new enterprises and some existing industry leaders.

There is no universal definition of the term, SME, which may vary in different countries and regions. However, generally, the size of the labor force or the value of assets thy possess are considered as indicators. As claimed by Frijns and Vliet (1999) [1], the number of employees in a company is an important factor for measuring the size of industrial enterprises, particularly in developing countries. They suggested two categories for small industries: micro-enterprises (1-9 employees) and small-scale industries (10-50 employees). Even though, the limit for the number of employees in a company to indicate a small or medium company varies in different countries. For example, in Mexico and Brazil, any company with fewer than 100 staff is considered an SME, in Australia, this number rises to 200 employees, and in the United States and Denmark, a company of up to 500 employees would be categorized as an SME (Hillary, 2000) [2].

The given definitions in most OECD countries are also based on labor figures where 500 employees are considered as the upper limit of the SMEs. On the other hand, the definition most commonly accepted and used nowadays in that of Eurostat of 19 European countries states that an SME must have no more than 250 employees. Manufacturing and services of SMEs are also considered in various scope within this definition (OECD Report, 2013) [3]. Another distinguishing feature of an SME is whether it is an independent organization or linked to a larger enterprise or group. Above all, the management structure also influences the classification of SMEs in some countries (OECD Report, 2004) [4]. The last OECD report published in 2013 clearly states that any enterprise can be called an SME if it fulfills the criteria for the number of staff and one or more of the financial criteria as provided in Table 1.

As stated above, the SMEs which are greatly important for national economies should able to stay on their feet and grow in a place of global competition through receiving the support of various funds provided mainly by the governments. That is the main reason for many countries to establish associations such as KOSGEB in Turkey where KOSGEB stands for the *Association of SME Development* which is responsible for supporting the SMEs. All nations provide support to their SMEs. There ise a necessity of an assessment methodology in oderd to validate and verify the fund distribution processes. In the developed countries, a well-structured information system is set up to follow the fund distribution programs as well as the progress along with the use of these funds. This makes it easier to carry out the respective evalutions of applicants. However, in the countries such as Turkey, there has not been a fully integrated IT system between the government and industry and business community yet. Therefore, an industry independent and separate assessment system is employed which may lead to several problems such as the inadequate distribution of funds among the sectors as well as a waste of resources in the areas which

Table 1 SME definition by European Union (OECD Report, 2013)

Enterprise category	Headcount	Turnover (€)	or	Balance sheet total (€)
Medium-sized	50-249	≤ 50 million		≤ 43 million
Small	10-49	≤ 10 million		≤ 10 million
Micro	< 10	≤ 2 million		≤ 2 million

may require less attention. This clearly requires an extensive study on defining a well-suited funding and assessment system which is also one of the major motivations of this research.
Note that, the SME support in Turkey Is carried out by KOSGEB. Currently, the funds are distributed through various programs and respective assessments carried out by institutional procedures.

KOSGEB estimates that the number of enterprises considered SMEs has remarkably increased to approximately 3,500,000 in the last five years (KOSGEB, 2019) [5]. On the other side, considering the limited amount of support funds available, providing funds on adequate by *as-needed* bases become very critical. Here the main question is to determine what support should be given to which enterprise? The funds will not produce the desired output (objectives of the funder providers) if they are arbitrarily provided to anyone who asks for them. By being aware of this, KOSGEB continuously seeks alternative support programs to increase the expected benefit for the enterprises. The project-based support system is one of these. This program has now become the leading SME support system in Turkey. SMEs should generate a project and indicate that the results of the project contribute to the development of the enterprise by increasing productivity, flexibility, mobility, profitability, service time, quality, and so on. The qualifications required by KOSGEB for project-based support are a strong financial structure and a history of successful completion of previous projects carried out by the claimer.

Similarly, KOSGEB implements more than 30 different support programs. The current assessment system employed is designed as a manual review system and it is easy to assess various enterprises at the same standard. However, it is very difficult to install a system to monitor the post-support state of SMEs. Since KOSGEB is the only agency that employs SME assessment and selection criteria, it was considered to be important to review its structure as well as support related operations for the success of this study. During this analysis, it was found that one of the basic tools used by KOSGEB to manage the support programs is the Beneficiary Situation Detection Form called YDTF.

Currently, each applicant fills in an SME Statement Form, providing respective information to find out whether or not they can be classified as an SME. If approved, they are then asked to fill in the Beneficiary Situation Detection Form (YDTF). The information given by the applicant in this form is reviewed by the experts and categorized into one of four groups (A- Micro, B-Small, C-Medium, and D-Large) in accordance with enterprise characteristics. The respective support is granted following the results of this assessment.

This classification is carried out using a set of criteria developed by KOSGEB through several years of experience. Interview with some of those experts indicated that the funding algorithm based on the classification of SMEs under these four groups makes it difficult to catch up with socio-economic developments over time, as well as making it difficult to perform the assessment in harmony with the present conditions. Furthermore, as stated above, having the fact that the number of enterprises falling within the scope increased more than eight times (from 400,000 to 3,500,000) within a very short period (in five years) also makes it difficult to manage the support programs with the currently available human resources. This obviously creates a negative impact on the performance and efficiency of the manual assessment and monitoring. A Computer-aided intelligent assessment system seems to be essential to remove this negative impact as it may clearly highlight the effectiveness of the assessment programs with limited funds available.

Similarly, several countries have developed and installed assessment systems aligned to their own national economic vision. Countries also manage to solve this problem to some extent by making their relevant agencies work in coordination and cooperation with each other employing a certain but common assessment system on a single database. Furthermore, it is claimed that if recently developed information technologies such as cloud computing are adapted to the infrastructure of such agencies, their systems would be more functional and the need to install an assessment system specific to an enterprise or sector could be minimized (Mell and Grance, 2011) [6]. For countries where such infrastructure is not available or is in the process of being developed (as in the case of Turkey), manual methods are utilized. Note that the lack of some competency-related data prevents effective assessments. Although some simulation studies like the one proposed by Dragic and Sorak (2016) [7] are carried out to define and predict SME data for the assessment, the right set of data is always subject to the effectiveness of the models utilized which are not easy to validate. This is also valid for some studies limited in scope and bounded by implicit requirements (see for example Emebo *et al*., 2017) [8]. It is believed that the framework proposed in this study may be a good reference for handling competencies for better assessment along this line.

The proposed assessment model focusing on certain competencies could be effectively adapted to the distribution of support provided by agencies, and make an important contribution to the installation of a flexible and dynamic fund management system. It may also be used to help SMEs increase their performance and industrial productivity in the medium and long terms as well as to monitor the sustainability of productivity with valuable and important feedback.

In the proposed model five basic modules have been developed to assess and measure the competencies of SMEs as explained below. For the sake of clarity, a literature review is provided first.

2. Literature review on SME assessment

There have been various assessment studies presented in the literature some of which are discussed below.

Sohn *et al*. (2007) [9] suggested a Structural Equation Model (SEM) based on mainly financial performances and management of technology for granting the respective supports to SMEs. Direct and indirect relations between technological and financial indicators are established and analyzed. Similarly, Xiao-hong *et al*. (2008) [10] concentrated the financial parameters and proposed an evaluation index that measures and evaluates the performance of funds provided to small and medium-sized enterprises in China. This study clearly indicates that the size and quality of an enterprise have a positive influence on the growth rate and record time of the enterprise, whereas the status of ownership does not have much effect. In terms of financial dimension factors, *solvency* was proven to have a negative effect on the business progress.

Moon and Sohn (2005) [11] proposed an evaluation model for distributing governmental funds by performance data using the decision tree method and data envelopment analysis. Consequently, they proposed a fund management system through an intelligent probability-based approach. Similarly, Yang (2006) [12] developed a *technical efficiency index* for SME assessment in Korea using data envelopment analysis (DEA). In this study, the eligibility of the SMEs for state funds is decided based on this index and the effectiveness of the program is analyzed through a comparison of enterprises both supported and not. The analysis in this study is restricted to efficiency, but it can be considered to serve as a starting point and light the path for more comprehensive analysis. Sohn and Kim (2007) [13], on the other hand, developed a random effect-logistic regression model using financial and non-financial factors in order to estimate the performance of SMEs that are supported by the government but do not fulfill their commitments. They identified that SMEs that did not fulfill their commitments often encountered refund delays, cheques bouncing, non-commercialization of products, or poor management. Similarly, an approach aiming to monitor SMEs as being part of an integrated assessment and fund management system is presented.

Ying and Li (2009) [14] presented an evaluation model based on both fuzzy logic and Analytical Hierarchy Process. They used both quantitative and qualitative data analysis in especially, evaluating innovation capability. Five evaluation stages such as *perfect*, *very good*, *good*, *medium* and *poor* were identified for each criterion to constitute a fuzzy matrix in assessing the innovation capability of Shaoxing Textile Enterprise Group. A similar study to assess the innovation capability in Austria is provided by Kaufman and Tödling (2002) [15]. Ahmad and Qui (2006) [50] also employed both AHP and DEA to measure enterprise manufacturing performance. In general, this study was limited to the re-evaluation of SME performance but did not provide any information about a support providing model. Innovation was also the main focus of the study carried out by Cheng and Wang (2009) [16] who studied destructive innovation evaluation and risk analysis in SMEs yielding the result that destructive innovation has an important role in survival in competitive environments.

Wang (2008) [17] provided a different but statistical approach taking the effect on external environmental factors for SMEs' living conditions into account. Six main factors mainly, external environment economy, politics, technology, social culture, human capital, and natural sources were examined using Structural Equation Model (SEM), Fuzzy Analytic Hierarchy Process (AHP), and Main Component Analysis (MCA) with the results of 12,000 surveys resulting that SEM performs better in comparison to other two.

Some of the research along this line produced performance assessment systems such as those carried out by Hvolby and Thorstenson (2001) [18], Barnes *et al*. (1998) [19], Hudson *et al*. (2001) [20], Delisle *et al*. (2004) [21], Brem *et al*. (2008) [22], Hanif and Manarvi (2009) [23], etc. Those provide assessment systems with little differences in the focus of the research or the methodology implemented. Some take delivery time, delivery duration, capacity ratio, quality levels, and cost accounts whereas others concentrate on strategic objectives or institutional control mechanisms. While some of them utilizing computerized technology such as expert systems, some implemented face-to-face meetings, some concentrated on a balanced scorecard approach. Some of those such as Kim *et al*. (2008) [24] implemented an adapted learning network to support the assessment process by examining various factors based on products and administrative properties. Some researchers were very keen on performing the comparison of performance modes provided in the literature (see, for example, Abouzeedan and Busler (2004) [25]. Note that in those studies, attention was paid not only to financial criteria but also to all criteria affecting the performance of the SMEs. Hanif and Manarvi (2009) [23], on the other hand, focused on quality, productivity, innovation, and investigation of learning initiatives. A hierarchical cluster analysis was conducted using the K-means algorithm. An interesting remark was provided by Ozturk and Coskun (2014) [26] by noting that the balanced scorecard was not an effective assessment tool for banking if it was not used properly.

Lin and Tong (2010) [27] constituted a two-step credit rating model using the Cox model and Support Vector Machine (SVM). They classified SMEs in Taiwan using a two-step model and presented that the accuracy rate was better than existing gradual credit rating models.

There have been some studies on assessing the organization for other purposes not focusing the attention on funding, rather identifying areas to be improved in comparison to others. Some of them are discussed below.

Little research such as the one provided by Katwalo (2006) [28] concentrated on the competency improvement of SMEs. SMEs in England were studied in terms of foreseen competency improvement capabilities. A brief description of competency and general information about competency improvement was introduced. Existing models were compared and factors making it easier to understand competency improvement were discussed. Although SME competency was the main focus, little information is provided in conjunction with the support assessment program.

Cassell *et al*. (2001) [29] studied the effectiveness of comparison methodologies designed to improve SME benchmarking. The most effective comparison factors were identified as financial indicators, customer satisfaction, and quality of products or services. But the focus of the assessment was not on providing support to improve the areas requiring improvement.

Vanhoof *et al*. (1995) [30] developed an agent-based information system. They evaluated within the context of Strength-Weakness-Opportunity-Threat (SWOT) analysis which is an important tool for identifying the strategic objective of any organization.

Fernandes *et al*. (2006) [31] applied the balanced scorecard approach using a systematic structured methodology in a case study. They claimed that SMEs in Britain's manufacturing industry had several problems. The right approaches and methodologies could help sort them out. They also listed the application results of the proposed method, and their experiences, successes, and lessons learned during the implementation process are highlighted.

The literature review provided so far indicates that enterprises, and especially SMEs, are evaluated in many different ways mainly employing the assessment criteria related to the field, structural properties, and respective specializations. The proposed methodologies include BSC, AHP, Fuzzy AHP, DEA, SEM, etc. (see for example Sohn *et al*., 2007 [9]; Moon and Sohn, 2005 [11]; Ying and Li, 2009 [14]; Hanif and Manarvi 2009 [23]). Furthermore, The Survival Index

Value Model (SIV) is unique to enterprise, and approaches such as the Two-Step Credit Rating Model, and the Structural Equality Model are implemented by improvements (as described by Abouzeedan *et al*., 2004 [25]; Lin and Tong, 2010 [27]; Romano *et al*., 2000 [32]).

In the assessment studies, making the actual status of an enterprise crystal clear is essential as well as some environmental circumstances. Although some general indicators are proposed for observing the enterprise status, the literature still highlights the need to identify a set of criteria specific to the enterprise under assessment for more detailed analysis. Moreover, it is shown that, in the assessment of enterprises, not only determining the criteria but also choosing the correct methods and approaches is also important.

3. Proposed methodology

The proposed framework is explained below with respect to its philosophy components and respective issues.

3.1 Understanding the competency of an organization

The topic of competency has a great variety of definitions. However, most of the definitions are focused on individual competency which is related to a person having sufficient knowledge and skills to carry out a certain responsibility. Mostly, competency is considered as the basic requirements to be satisfied by the employees in an organization.

The term *competency* was first appeared in the paper of R.W. White in 1959 introduced for performance motivation. Later, it has been popularized by other researchers especially in performance improvement activities after the 1970s (Audrey, 1989) [33].

Although there have been some studies on competency as an individual, there is little research going on for the competency of the enterprises. This is one of the reasons for aiming to examine and assess the competency of the organizations, especially of the small and medium enterprises (SMEs) in this study. Organizational competency can be defined as “the capability of an enterprise to adapt itself to changes in technology, methods, and methodologies, processes, managerial approaches as well as the changes in customer behavior”. The best competent organization is assumed to be the one well capable of managing the change and dominate the market in any aspect related to the business.

Hitt *et al*. (2015) [34] defines competency as the combination of both resources and capabilities. They state capabilities that are valuable, rare, difficult to imitate, and difficult to substitute as the core competencies which would be the baseline to the strategic competitiveness.

In this study, this definition is taken as a baseline and the competency is defined from the organizational point of view as such that the technical competency, financial standing, strategic restructuring, and intellectual capacity of the enterprise, as well as its ability to utilize those, are considered to be the core competency areas. Additionally, it is accepted as important to focus on the ability of the enterprise to convert its commercial and managerial resources into a benefit, and to what extent that it could use these qualities effectively and efficiently. The model proposed in this study, therefore, focuses on these areas.

3.2 Competency assessment approach of the proposed model

The concept of competency that forms the foundation of the proposed model is an indicator of any aspects of the enterprise such as background, knowledge, applications, approaches, methods, and the most developed equipment, etc. As shown in Fig. 1, these capabilities have been grouped and collected under five evaluative areas. For each of these, the capability and skills to be assessed have been uniquely defined. In other words, the proposed model so-called ASME (Assessment of Small and Medium Enterprises) is made up of five main components such as:

- Technological competency,
- Financial competency,
- R&D and innovation competency,
- Strategical competency,
- Intellectual competency.

The goal of each of these components is to measure the competency of an enterprise in a certain aspect. Setting out these five areas of competencies, the factors having the most important or the biggest effect on the development and improvement of the enterprises are taken into account. A nested and staged representation (leveled architecture) is introduced. A scoring system is also developed in order to measure the general status of the SMEs under assessment using the ASME Model.

The general status of the enterprise under assessment is first evaluated through a pre-assessment procedure. That is to identify the business type and respective business operations to be assessed. Note that each component and respective levels specified by the proposed model are weighted to validate adequate funding for the most needed areas.

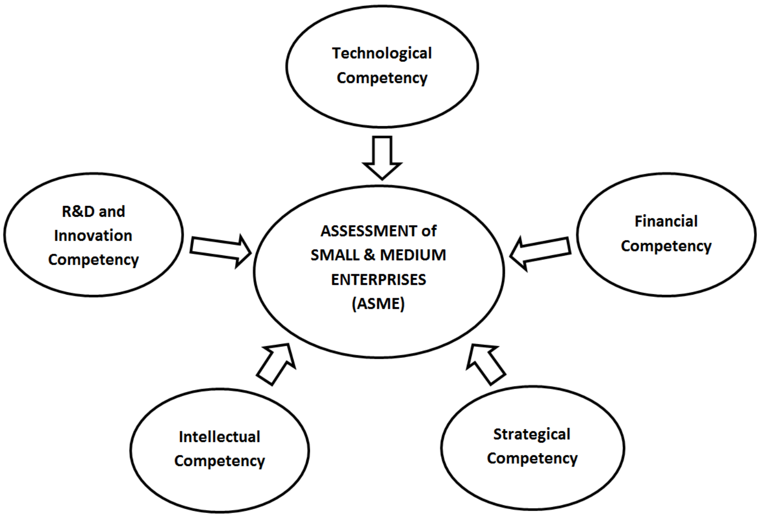

Fig. 1 Components of proposed generic model for assessment of SMEs (ASME)

In the proposed model, each area of competency has been divided into six levels where each level has a predefined requirement within the scope of related competency at that level. The main objective of the model is to match the existing state of the enterprise to the most suitable level of the competency. The reason for separating the areas of competency into levels is to create a nested assessment system in the organizations as shown in Fig. 2. In the proposed nested structure every level of competency naturally covers the related characteristics of the lower levels. For example, the sixth level indicates that the SME is to be in the highest degree of competency and means that the SME has all the qualities of the levels.

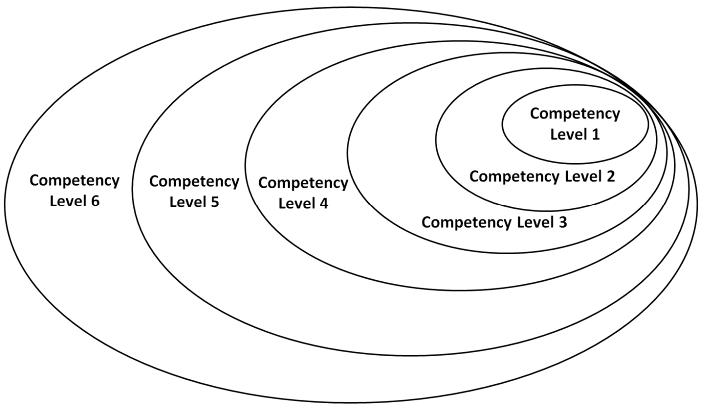

Fig. 2 Nested illustration of Competency Levels

For any SME, the important thing is to be able to develop itself in respective areas of predefined levels of certain competencies producing the point of competency scale for that enterprise. This unique point of the scale allows the provision of support in order to establish a course of action in conducting the assessments. If the enterprise that cannot fulfill one or more of the criteria for a particular competency level is not considered to move into a higher level, and cannot claim the support and funds assigned to that particular level.

A measurement scale between 0 to 100 has been created in order to identify the competency 6 levels of the SMEs as such that 10 points indicate the level score (*LS*) that the enterprise has the first and weakest level of competency (level 1) whereas 20, 40, 60, 80 and 100 points are assigned as the level scores to the subsequent levels respectively.

As an example of a score-matching card, sub competency of Technological Competency is illustrated in Table 2. The same matching card is used for each five core competency which is proposed in the model.

Note that the in Score-matching card, each assessment factor (*AF*) determines the respective competency level of the enterprise as *retained level* (*RL*) since each level and operational capability has its predefined scores. After summing up the scores obtained for all assessment factors, the generic component competency score is calculated by dividing the total value by the number of factors assessed. Here in the example, some most known assessment factors are used for IT Infrastructure as seen in table 3. In order to establish which assessment factor will be in which level, the level identification table as it is seen as an example in Table 3 will be used. The table is arranged that each higher level encapsulates the other lower levels. Every five key competencies with sub-competency have a similar identification card but due to paper limitation rest of the tables could not find a place in this study.

In the Table 3, the scope of each level has been described using general terminology. This is so that a generic and flexible model that covers different sectors and SMEs can be established. Considering the recent technological transformation as well as developments, not many enterprises will have so much love competency indicated by the first level. However, this level is still kept in this approach for the sake of completeness and wider coverage of the assessment system. In order to sustain and validate the applicability of the model a flexible structure is generated which has high potential to be updated according to the requirements of the fund providers and strategic objectives of funding.

Table 2 An example score-matching card for IT system as a Sub competency of Technological Competency

	Level 1 (0-10)	Level 2 (10-20)	Level 3 (20-40)	Level 4 (40-60)	Level 5 (60-80)	Level 6 (80-100)
Level → ↓ Assessment Factors (Af_i)	No information technology (LP_1 Point: 10)	Independent software use (LP_2 Point: 20)	Integrated electronic data exchange (LP_3 Point: 40)	Integrated developed electronic data exchange (LP_4 Point: 60)	Software-based decision making (LP_5 Point: 80)	Automated decision making (LP_6 Point: 100)
Af_1 Operation systems	Retained level (RL_1)	-	-	-	-	-
Af_2 Accounting programs	-	-	Retained level (RL_3)	-	-	-
Af_3 MRP System	-	Retained level (RL_2)		-	-	-
….	-	-	Retained level (RL_3)	-	-	-
Af_n ERP system	-	-	-	-	Retained level (R_5)	-
Level score	$LS_1 = \Sigma LP_1$ $LS_1 = 10$	$LS_2 = \Sigma LP_2$ $LS_2 = 20$	$LS_3 = \Sigma LP_3$ $LS_3 = 40 + 40$	$LS_4 = \Sigma LP_4$ $LS_4 = 0$	$LS_5 = \Sigma LP_5$ $LS_5 = 80$	$LS_6 = \Sigma LP_6$ $LS_6 = 0$
Sub-competency of technology (SC_2)	$SC_2 = \sum_{i=1}^{6} LSi \,/\, \#Af$					

Table 3 An example level identification table for IT system as a Sub Competency of Technological Competency

Technological level	Explanation
Level 6 Automated decision making	An SME at this level is at the most developed level of information technology. Every sort of work and data storage is carried out on a cloud server and satellite connections are used to allow for the fast buying and selling of data. In terms of hardware, tools are not used except for data entry and screening. ERP and MRP type programs are integrated and restored smart systems can carry out every kind of work without human intervention. Managers can access any information they want instantly (with devices such as mobile telephones, tablets and computers, etc.). The system has a very flexible and smart reporting function. Employees can access and carry out their work without being in close proximity to the system by connecting via mobile phones or personal computers. Every hardware and software infrastructure is in place to run unmanned manufacturing enterprises.
Level 5 Software based decision making	At this level, every kind of software used is integrated, and necessary data can be ascertained, used, and shared without human intervention. Using a fast network infrastructure system, the software can share data with systems in other regions, and when necessary can find data on the internet to be used with smart decision-making mechanisms.
Level 4 Integrated developed electronic data exchange	At this level, many programs are used across a network and data can be shared. As with general-purpose software, specific purpose programs can be integrated and a central data repository can be used.
Level 3 Integrated electronic data exchange	Programs that are used generally to reduce a company's workload come under this level. Programs specific to the sector or enterprises are used independently. They can be used in a network and to provide inclusion of electronic data handling.
Level 2 Independent software use	At this level, there are independent programs and computer hardware. The programs are used generally for the running of the enterprises rather than for any particular purpose.
Level 1 No information technology	At this level, no form of computer hardware or programming products is used for any purpose in the enterprises. Every form of calculation, drawing, and planning work is performed by hand.

After defining the competency score for all sub-components of Technological Competency and five components of the model, the overall competency score (Competency Grade) of the enterprise is calculated by multiplying each main component competency score with its respective weight values which is represented as α_i and adding them up. A case study in a valve manufacturing process is assessed for proof of the concept of the proposed model.

A competency function with the purpose of showing the degree of corporate competency is established as shown in Fig. 3. The following abbreviations are used for sub-components of Technological Competency.

- SC_1 Machinery suit; Machinery suit (infrastructure) weight: $\alpha_1 = 0.5$;
- SC_2 IT systems; IT systems weight: $\alpha_2 = 0.2$;
- SC_3 Manufacturing support operations; Manufacturing support operations weight: $\alpha_3 = 0.1$;
- SC_4 Storage & delivery; Storage & delivery deight: $\alpha_4 = 0.2$

Technological competency score: $TCs = \Sigma\alpha_i \cdot SC_i$

The other four components of the model are not considering any subcomponent. Note that the weights of the sub-competencies and main core competencies are defined by using SWARA (Step-wise Weight Assessment Ratio Analysis) methods which is one of the most used multi-criteria decision techniques (Keršulienė, *et al*. 2011 [35]; Zolfani, *et al*. 2013 [36]).

Table 4 indicates some examples of weighing schemes for different sectors. Note that these weight values are defined by a series of expert view studies using SWARA methods. However, the model does not impose these values, the assessor organization can define the respective values in accordance with their suitability and can be defined by a specific purpose. The model requires that the weight provided in Table 4 is to be multiplied by the level of competency of the enterprise yielding a score called *competency score* (CS).

Table 4 Competency weightings of selected sectors

Competencies \ Sectors	Mining	Energy	Construction	Manufacturing	Other services
Technological competency (*wtc*)	0.3	0.3	0.2	0.3	0.2
Strategic competency (*wsc*)	0.1	0.2	0.1	0.1	0.2
Financial competency (*wfc*)	0.2	0.3	0.3	0.2	0.2
Intellectual competency (*wic*)	0.3	0.1	0.3	0.2	0.2
R&D and innovation competency (*wrdi*)	0.1	0.1	0.1	0.2	0.2
Total weights	1.0	1.0	1.0	1.0	1.0

Weights for application in this study are imported from table 4 for the manufacturing sector. The calculation is carried out using a defined abbreviation as seen below:

- TCs – Technological competency scale calculated as overall of sub-components for Technology
  Weight of technological competency: wtc = 0.3
- FCs – Financial competency scale (will be accrued from related score matching card)
  Weight of financial competency: wfc = 0.2
- SCs – Strategic competency scale (will be accrued from related score matching card)
  Weight of strategic competency: wsc = 0.1
- $RICs$ – R&D and innovation competency scale (will be accrued from related score matching card)
  Weight of R&D and innovation competency: $wrdi$ = 0.2
- IC – Intellectual competency scale (will be accrued from related score matching card)
  Weight of intellectual competency: wic = 0.2
- OCS – Overall competency score

The SME corporate competency level is calculated by multiplying the degree of competency and the weights as such:

- Technological competency score: $TCS = TCs \cdot wtc$
- Financial competency score: $FCS = FCs \cdot wfc$
- Strategic competency score: $SCS = SCs \cdot wsc$
- R&D and innovation competency score: $RICS = RICs \cdot wrdi$
- Intellectual competency score: $ICS = ICs \cdot wic$

Competency function is then given by the following equation:

$$OCS = TCS + FCS + SCS + RICS + ICS$$

Defining OCS in this way indicates the enterprise has one of the following technological competency states:

$00.00 \leq OCS \leq 9.99$ → Very poor
$10 \leq OCS \leq 19.99$ → Poor
$20 \leq OCS \leq 39.99$ → Insubstantial
$40 \leq OCS \leq 59.99$ → Just enough
$60 \leq OCS \leq 79.99$ → Good/Perfect
$80 \leq OCS \leq 100.00$ → Excellent

Fig. 3 is the radar graph of different competency scores with a visual representation of the competency scale area to better understanding.

Each competency in the proposed model is assessed by measuring several assessment factors represented by Af_i. This is defined to be able to calculate the total level score as such. Retained level point of Af can be placed on those of existed levels in the table L_1, L_2, L_3, L_4, L_5, L_6 then each Af will get a Level Point that is symbolized by an abbreviation LP. Summing all assessment factors will be divide into several assessment factors used in the table.

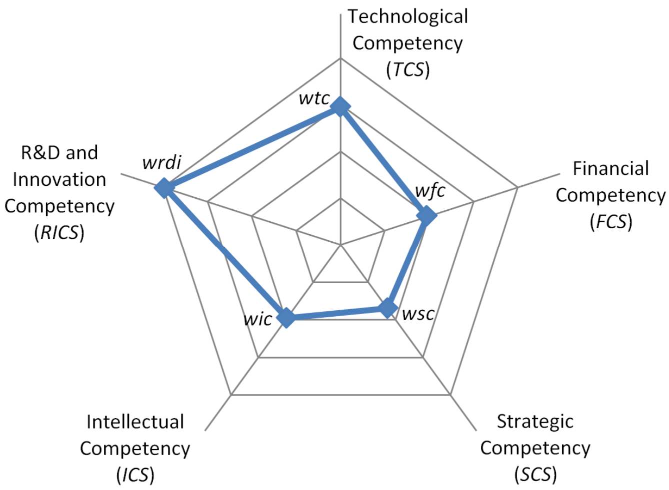

Fig. 3 Radar Diagram of SME Competency Scale

Based on this, each Competency Score (CS) will be calculated as multiplying each component score with its respective weight values and adding them up ($\Sigma\alpha_i \cdot SC_i$). For a more detailed assessment, a second alternative can be used by the assessor assigning another weight to each assessment factor. Since the existing study is only comprised of generating a framework model, it is not considered in this study.

3.3 Components of the proposed model

The SME competency assessment model comprising five core concepts that are introduced in a generic framework and the scoring system. The reason for identifying five areas of competency is clarified through supporting the idea by existing literature and scrutiny of the importance of them in terms of SMEs. A brief definition of each competency and the respective model elements with assessment tables are explained below.

Technological competency

The success of business nowadays is strictly related to the technological competency of the enterprise, particularly in the manufacturing industry. Companies are competing by their know-how and technology suits to facilitate their expertise for the sake of improving their power of competitiveness. This capability is even becoming more and more important especially with the introduction of Industry 4.0 (Sari *et al*., 2020) [37]. As such, studies in this area are no longer focus on just technology but are also associated with innovation and unmanned operational capability. Developments in technology get the ball rolling for innovative products and processes to spring up. The continuation of a company is now directly related to its ability to adapt to technological advancements. Medic *et al*. (2019) [38], highlighted the importance of advanced Industry 4.0 technologies in manufacturing and they provided several criteria to perform a digital assessment with respect to technological progress. They particularly pointed out the necessity of integrated software suite like ERP systems. The technological competency would not be ensured without taking this into account. IT capability is therefore directly linked to competency progress in this study. Moreover, faster and higher quality presentation of products and services by discovering and utilizing the domain knowledge through IT utilization. From the past to today (from the 1 revolution to the recently announced 4th one), technology, along with social, economic, and cultural factors, has become one of the components with the biggest influence on the change of societies. The introduction of new system developments and generation of the tools and machines fueled the agricultural revolution to digitalization. The transformation continues from industrial society towards the knowledge society. This kind of change and effect that technology brought about to societies led to various definitions and commentaries of this concept throughout history (Kibritçioğlu, 1998 [39]; Durand, 2004 [40]). On the other hand, the belief on "something that can't be measured can't be managed" has created the need for technology to be managed and adopted. Many studies on technology management in this line have become very popular (see, for example, Kropsu-Vehkapera, 2009 [41]; Cetindamar *et al*., 2009 [42]; Tekin, 2006 [43]).

In this study, a six-step scaling system for technological capability has been proposed to identify the level of the technological infrastructure of a certain enterprise. A hierarchical structure is proposed in such a way that each level includes the characteristics of all the levels below in the hierarchy. Besides, a set of criteria for each degree of competency within a level has been specified. The main aim of this is to define the competency level of an enterprise in terms of stated criteria at that level. Thus, the technological competency assessment is performed on the available foundational infrastructure. The core infrastructure is made up of a machine system that is effective in every area of production by directly adding value to the business. In order to increase the applicability of the model to different sectors and business branches, it is designed with a general assessment logic. Four core infrastructures (Sub-Competencies of Technological Competency Module) that are considered to have great importance in every sector are taken into account as such (Fig. 4).

- Machinery suit (infrastructure),
- IT Systems (examples are given in Table 2 and Table 3),
- Manufacturing support operations,
- Storage & delivery.

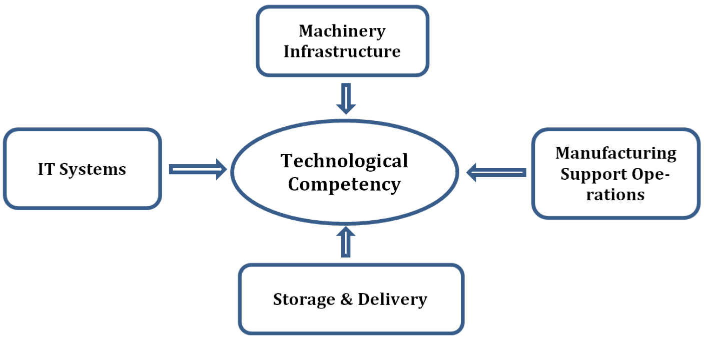

Fig. 4 Sub-Competencies of Technological Competency

In order to make the analysis and evaluation of the processes easier, an assessment Score-Matching Card has been created that the necessary and required information for each level is stored on this card. Note that, these cards are structured in a table format where every column highlights the levels of operational competence and each row indicates the available business operations/capabilities/systems such as machining, programming, etc.

As shown in Fig. 4, the technological competency is assessed by four sub-competency infrastructures stated above. These sub-competencies have been identified by considering the areas in business where technology has to be implemented. A basic weighting and scoring system is also proposed. As each level encapsulates the lower levels, the degree of technological competency increases level by level. A score for generic technological competency level is calculated by multiplying the level scores of the operating infrastructure as defined weights by experts similar to main competency weights.

Financial competency

As stated above, most of the SME evaluations are based on financial indicators with respective analyses. Due to quantifiable measures, this attracts the assessors to check out the corporate strength of any enterprise, especially SMEs. In business society, it is strongly believed that financial power indicates the continuum lifecycle of the companies in any nature. That is the main reason for relying on a financial indicator such as ratio analysis for the assessments. As financial ratio provides some information such as liquidity, indebtedness, and profitability of the enterprise it attracts not only the assessors but also other main stakeholders. For example, the banks or bankers use this ratio as the baseline for deciding on credits (loans) and perform risk assessments. In the scope of this paper, a different point of view and interpretation is presented on the ratios concentrating on the competency. With this in mind, Altman's (1998) [44] Z score model has been taken as a basis as it is also proven to be more consistent and correct (Altman, 2000) [45]. This model introduces a weighting scheme for analyzing respective financial ratios. His analysis is based on the relationship between assessment components which are experimented with a multiple discriminant method. Note that, this analysis predicts the financial ratio by several characteristics such as *safe*, *grey* or *distress* zones.

A level boundary table is created and financial position is scored according to the corresponding level of this table. First of all, financial data is analyzed and respective ratio values are calculated. They are then compared with the industry standards. This level-based analysis is expected to identify first and foremost state the enterprise's financial level and its respective score. The percentages for the levels have been stated in accordance with the conditions of the period subject to the assessment. In this study, the ratios have been leveled taking the difference out of standards. For example, if an enterprise ratio is more than 50 % away (below) from the industry standards, that enterprise is considered to be at the second level of competency whereas the sixth level indicates that the enterprise is well operating and is 50 % above the standards.

The level boundary table has been described before states that a level for each financial ratio is evaluated individually. As with the scoring of the other competencies, a score is given to each ratio using a scorecard and the level warranted. The Financial Competency score is calculated as the following.

Financial Competency Level Score = ∑ Ratio Score / #Ratio

By using the level competency score-matching card and listing the ratios from the leveling table that is similar to example table 3, it is clearly seen at which level the enterprise standing for its financial capability. The overall financial competency score is obtained by averaging all scores. The following factors are assessed under this component:

- Sales profitability,
- Asset turnover,
- Working capital ratio,
- Debt burden,
- Debt-equity ratio,
- Working capital turnover.

Strategic competency

Strategic management and planning are defined as the systematic way for an organization to reach its long-term objectives, the methods used in resource allocation necessary to attain these goals, and applications in the light of these methods. The strategy is seen as an administrative tool that provides innovation, advancement, and interaction with the business's environment and that keeps changes under control. It is hard for an enterprise that is not strategically strong to achieve satisfactory and permanent productivity and effective operations. Therefore, the evaluation of an SME's strategic competency is considered to be an important matter in the assessment. By been aware of this, Husseyin and Jahanzaip (2018) [46] proposed a conceptual manufacturing framework that is structured by three elements as Ideal, Strategy, and Architecture in order to sustain a continuous business. They considered strategic planning, being the combination of transformation sustainability and competitiveness as the core element. However, measurement in strategic competency is important but extremely difficult. Taking the internal and external conditions of enterprises into account, it is important that the short and long-term plans of an SME are correctly set up. While preparing these plans, appropriate strategies should be employed, and these strategies need to be well managed. For an SME, first, the mission and vision and then the goals and aims of the business must be identified. Then the strategies need to be stated according to the business structure and market position, and in time, updated accordingly (Ulgen and Mirze, 2004) [47].

As has been done for the other competencies, a six-step assessment table has been created for strategic competency assessment as well. The proposed strategic competency model is expressed in terms of environmental analysis, strategic thinking, planning and implementation, department-based operations, control evaluation, and continuous improvement within this scope as well as key performance indicators. The following factors are considered to be sufficient in performing the assessment for this type of competency (for more precise calculation, each factor can be weighted as well):

- Environmental analysis,
- Strategy formulation,
- Planning and implementation,
- Department constitution,
- Control and evaluation,
- Feedback and continuous improvement.

Similar to other components of the competency model, the strategic competency will be scored using a leveled table. Using the scorecard, it will be determined whether or not the parameters of strategic management, analysis of environmental conditions, strategy creation, implementation, and control assessment are in place or not. The score-matching card is used in a similar manner. Each level is marked depending on the score achieved through the control of whether the necessary processes are being fulfilled or not. As with the other competency modules, it is possible to rearrange the scoring of the strategy levels in the scorecard according to the situation or strategy of the business that will use the leveling model.

Intellectual competency

The world is on the edge of the information era. It is now very clear that the effective usage of knowledge in operations becomes more important, especially, with the transition from industrial to the information revolution. The information with respective knowledge has a direct impact on many areas such as company strategies, corporate performance management, and customer satisfaction. This is also very much related to the transformation of organizational culture as revealed by Draskovic *et al*. (2019) [48]. With this in mind, one of the most important issues corporations experience today is how to use the right knowledge in the right place at the right time and in the right way. That is the main reason for taking knowledge management as one of the main indicators of institutional competency. The companies without strong knowledge management capability it is extremely hard to solve the problems. An SME with strong corporate culture and effective utilization of knowledge and information systems is considered to develop its related competency.

A similar six-step scaling system has been created for evaluating intellectual capital as well. The levels are stated in six stages starting from the first level. The first level shows the weakest position of an enterprise's intellectual competency whereas the sixth level shows the highest degree of intellectual competency. Similarly, a scorecard method is used and a score is defined for each level of intellectual competency. In the proposed leveling system for intellectual competency, each level will be assessed from five perspectives such as:

- Information management
- Education level,
- Career management,
- Process and improvement, and
- Generation of new ideas.

In the scorecard, the first and lowest level is defined as *implicit knowledge possessed*, the second level as *knowledge providing*, the third, *understanding of knowledge*, the fourth, *analysis of knowledge*, the fifth, *evaluation of knowledge*, and the sixth and most developed level as c*reating of knowledge*.

The scoring of intellectual competency will be carried out in the same fashion as the previous competency modules by evaluating the state of the enterprise in each intellectual dimension according to the definitions which are tabled and marking the level on which an enterprise possesses on the scorecard. After every intellectual dimension has been marked, the level scores are summed up and divided by the number of dimensions. Thereby, by multiplying the result by the intellectual competency weights, an intellectual competency score to be used in general assessments is obtained.

Research & Development (R&D) and Innovation Competency

Global competition among corporates has inevitably created the need for businesses to conduct R&D and innovation in business (i.e. on products or processes). Due to the importance attached, R&D and innovation have become an important necessity all over the world for the growth of SMEs and the marketing of more products or services. Furthermore, over the past few years in developing countries, the studies related to entrepreneurship attracted the attention of fund providers and the support of new entrepreneurs has increased. Businesses that can increase their productivity could gain a competitive advantage in the markets. Increasing productivity depends on gaining competence in innovation on a global scale (Chen *et al*., 2009) [49]. Consequently, the existence of R&D and innovation in SMEs and to what degree they are effective has come forth as important criteria in searching out a better assessment model and it is considered that innovation and R&D, evaluated as an important area of competency.

Innovation and R&D mean turning an idea into a marketable product or service, a new or developed manufacturing or distribution method, or a new social service method. For successful innovation and R&D management, the respective innovation strengths of businesses must be explored and evaluated.

For this reason, as with the other competency tools above, the potential and performance of a business through measuring the company's R&D and innovation competency and capacity are considered to be taken into account. Similar to the others, The R&D and innovation competency assessment model has also been constructed using a six-step leveling table as with the other competency modules. Each level is examined from three core perspectives defined as *commercialization*, *R&D and innovation culture*, and *R&D potential and structure*. The definitions of these three areas have been leveled separately in a nested structure as defined earlier.

As with the previous competencies, a scorecard is used for the scoring of R&D and innovation competency. According to the scorecard, technological competency, strategic competency, and intellectual competency other competencies, and the R&D and innovation structure, scoring will be done determining will be used in the measurement of this competency. In addition to these, R&D and innovation structure will be scored with the assessment table mentioned in the previous sections. Thus, the R&D and Innovation structure will be evaluated with three competencies that are components of the proposed model.

The scoring of R&D and innovation competencies in enterprises uses a different approach than that of the other competencies. In this competency, it is necessary to consider the situation of the technological, strategic, and intellectual models. Therefore, the scores previously obtained for these three competencies are also added to the R&D scoring table. In addition to this, R&D potential and infrastructure, R&D and innovation culture, and commercialization will be used in the scoring. However, the model has a flexible structure and an enterprise using the model can create its assessment table and update the proposed table as necessary.

4. A case study: Implementation of the proposed assessment model

The validity of the competency model proposed in this study is illustrated by performing an assessment of an enterprise operating in the metal industry. KAYALAR ARMATUR of KAS GROUP where the model is implemented is a medium-sized valve manufacturer. Although, the proposed model has a general structure; this application provides information regarding the applicability of the model in the manufacturing sector. As stated earlier, the model requires sector-based weight values to indicate the importance of each component of the model for a defined sector. The competency weights given in Table 4 for the manufacturing sector are used.

The assessment is carried out for each competency using the scorecards explained earlier in related table 2 that is exampled on IT System as a sub competency of Technological Competency.

By comparing the information obtained for the company with the competency level descriptions, the retained level for each assessment factor for each competency is identified and marked on the scorecard. A competency score for each competency is calculated and by adding together these scores for each operation and dividing by the number of operations. Note that the four sub-competency of technological competency is previously calculated to find the score of technological competency.

The total of these scores states the enterprise's overall competency score which is calculated to be:

$$Overall\ Competency\ Score\ (OCS) = TCS + FCS + SCS + RICS + ICS$$
$$OCS = (TCs \cdot wtc) + (FCs \cdot wfc) + (SCs \cdot wsc) + (RICs \cdot wrdi) + (ICs \cdot wic)$$
$$OCS = (31.75 \cdot 0.3) + (56.66 \cdot 0.2) + (23.33 \cdot 0.1) + (24 \cdot 0.2) + (33.30 \cdot 0.2)$$
$$OCS = 9.525 + 11.33 + 2.33 + 4.8 + 6.66$$
$$OCS = 34.645$$

$$20 \leq OCS \leq 39.99 \quad \rightarrow \quad \text{Insubstantial}$$

Considering the scale created earlier, since the company score is between 20- 39,99 then, it can be defined that this enterprise competency is insubstantial. Company score together with respective module scores shown in Fig. 5. After find to a retained level of each assessment factor for each competency TCs is calculated and then to find the competency score weight of related competency is used. Weight values are defined by the experts who work operationally in the sector of the company.

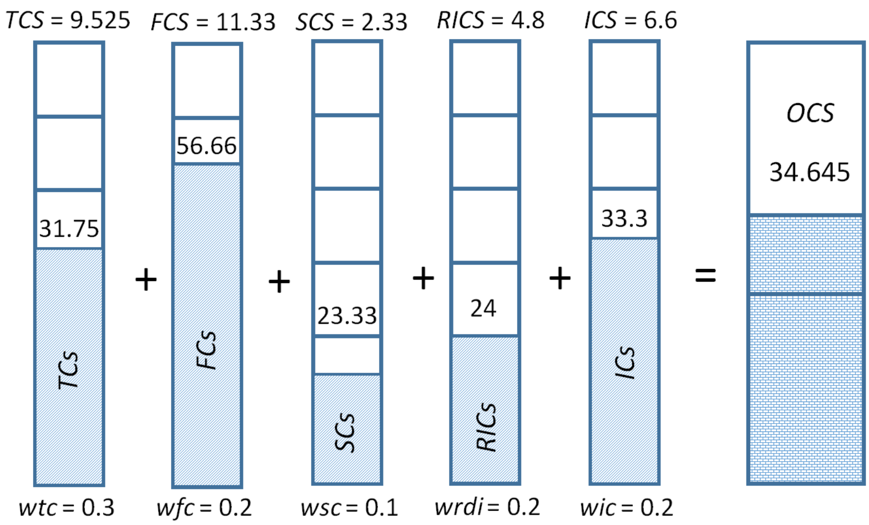

Fig. 5 Visual Representation of the competency assessment of KAS VALVE Inc.

In the general competency assessment, since the KAS VALVE Inc. is a manufacturing enterprise, the highest weighting it received for any of the five competency components was 0.3 for technological competency. As for the four sub-competencies that make up technological competency, 0.5, the highest weighting, has been applied to machine infrastructure, with 0.1, 0.2, and 0.2 being applied to the other areas respectively. In the technological competency assessment, the four sub-competencies scores were found to be as follows:

- Machine Infrastructure Score: 33.3
- Manufacturing Support Operation Infrastructure Score: 35
- Storage & Delivery Infrastructure Score: 28
- IT Systems Infrastructure Score: 30

Taking these scores and multiplying them by the relevant weightings gives a competency score of 31.75 for technological competency.

$$TCs = 33.3 \cdot 0.5 + 35 \cdot 0.1 + 28 \cdot 0.2 + 30 \cdot 0.2 = 31.75$$

This score shows that the enterprise's technological competency is at level 3. Similarly, the scores 56.66, 23.33, 24, 33.3 were calculated for financial, strategic, intellectual, and R&D and Innovation competencies respectively. Thus, the overall competency level of the enterprise has been defined according to a value that is calculated and represented above as OCS = 34.645.

KAS VALVE Inc.'s strongest area of competency with a score of 56.66 contributing to the overall competency level by 11.33 is financial competency. The next strongest competency is technological competency with a score of 31.75 (overall score of 9.525), which is due to the enterprise being a manufacturing company. This shows that after the enterprise's financial infrastructure, its technological infrastructure is strong. Even though the R&D and Innovation competency score is low, it is a competency that is necessary at certain levels for a manufacturing company with a competency score of 6.6. It is seen that the strategic and intellectual competency scores of 2.33 and 4.8 are comparatively low. Therefore, it is predicted that KAS VALVE Inc. would not be able to apply for support from KOSGEB in strategic and intellectual areas as support is classified according to certain scores. It is recommended that the assessed enterprise increase its strategic and intellectual competency by strengthening any missing components, or by securing support to strengthen these competencies. The strengthening of weaker competencies can also have the effect of raising other competencies to higher levels.

5. Conclusion

SMEs whose number is remarkably increasing day by day can also be seen as the locomotive of economies in most of the countries. Therefore, it requires a considerable effort to make them operate efficiently and effectively with compatibility capabilities. They are mostly supported by the official agencies to sustain the level of competency possessed.

With the increase in the number of various supports offered by government authorized organizations such as KOSGEB, the fund utilization and effectiveness of support programs are the main concern. Due to the environmental, political, and social effects as a result of globalization, it is not easy to sustain competitive advantage. Since, the number of SMEs in need of government funds increasing, defining a more selective method and fair distribution of these limited funds is at the top of the agenda. Giving the right amount of funds to the right enterprise is of great importance for increasing both the benefit to the enterprise itself and also to the country.

It is known that every country has its own methods for assessing the benefit of funds provided to enterprises according to its political and economic conditions. In evaluations that have been carried out, it is seen that these kinds of problems have been over overcome due to strong integration between government organizations, particularly in developed countries. Many problems can be solved from the beginning through the collective process of data collection, sharing data, and use of highly integrated automation systems. In many countries, the assessment of companies who wish to receive funds is carried out by experts using a variety of formulas. This process cannot identify the extent of the benefit of the funds to an enterprise just as it cannot test the strength of the enterprise applying for the governmental funds. Therefore, it is possible that much of the funds given by the government are in fact used by enterprises that cannot reap the expected benefits. Besides there is a need for information gathering and processing capability on how effective the given supports are to the enterprises. Hence, a custom made monitoring system is required for each country.

In this study, it is demonstrated that in reality, the desired results of an assessment will not always be obtained by just considering the financial data. Initially, a generic evaluation framework is defined. Within this framework, it is expected that the fund distribution schemes need to be improved through not only concentrating financial ratios but also other capabilities such as technological, strategic, financial, R&D as well as intellectual capabilities. Therefore, governmental organizations such as KOSGEB in Turkey that provide a variety of funds and support to enterprises need more effective and dynamic assessment systems. For the creation of such systems, it is first necessary to well-understand the competencies of enterprises from different aspects and measure those.

Implementation of the model in an actual enterprise indicated that the model can be easily employed and there is no difficulty in collecting the required information to perform the assessment.

The proposed model can easily be improved and turned into a systematic structure through a programming language to considerably facilitate the assessment of applications made by millions of SMEs. It is foreseen that such an agent-based framework model also can considerably facilitate the following secondary objectives:

- Determining relevant performance indicators to accomplish dynamic analysis of the state of SMEs.
- Determining the SMEs to be supported and the amount to be provided.
- Estimating what support will bring what kind of benefits, and building an infrastructure to plan the next support under such estimations.
- Displaying what types of support provided SMEs with more successful results.
- Making suggestions to SMEs on how to use the support they receive in a better way and providing SMEs with the computer-assisted distant training courses.
- Analyzing clusters of SMEs by industry or assessing SMEs within an industry.
- Analyzing how the support efficiency by industry should differentiate per industrial needs.

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Study of load-bearing timber-wall elements using experimental testing and mathematical modelling

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A B S T R A C T

Combining timber and glass in the wall elements of the building envelope with the proper orientation of such transparent façade elements enables the utilization of solar energy for heating and internal illumination of the building. However, the asymmetrical layout of timber-glass wall elements in such buildings can result in problems with the horizontal stability of the structure, so their participation to load-bearing capacity of the structure is usually neglected. The study deals with solutions for such elements as horizontal load-bearing members with proper connection details. First, specifically developed timber-glass wall elements were experimentally tested under monotonic and cyclic horizontal point load, and further in combination with classical timber-framed wall elements implemented into special single and two-storey box-house models, which were further experimentally tested on the shaking table. In the second part as the main goal of the study, a quite simple mathematical model of the box-house prototypes is developed using a fictive diagonal element for simulating the racking stiffness of the bracing timber-glass wall element. The calculated results for the 1st vibration period are compared with the previously measured experimental results to prove an accuracy of the developed model. Finally, a linear time-history calculation is done as a sample presentation of the developed mathematical model using Landers acceleration spectrum. The developed mathematical model enables a simple and effective seismic response calculation of timber buildings considering the developed timber-glass wall elements as load-bearing bracing elements against horizontal load actions. The model can also be recommended for using in further parametric numerical academic studies analysing the influence of various parameters.

A R T I C L E   I N F O

Keywords:
Wall elements;
Timber;
Timber-glass building;
Stiffness;
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1. Introduction

Climate changes of the last few decades do not only encourage research into the origins of their onset, but they also mean a warning and an urgent call for a need to remove their causes and alleviate the consequences affecting the environment. Eco-friendly solutions in residential and public building construction remains our most vital task, whose holistic problem solving requires knowledge integration [1]. Therefore, the domain of energy consumption is witnessing a worldwide trend whose aim is to reduce primary energy consumption and greenhouse gas emissions. Consequently, many investigations have been carried out towards 100 % renewable and sustainable energy solutions in many different areas [2-5]. Constructions are, besides the fields of transport and industry, one of the main users of the primary energy from fossil sources. However, it is important to set out that residential buildings forming 70 % of the total buildings' surface consume and are responsible for 63 % of the total energy demand required to satisfy the requests of the hosing stock [6].

Moreover, the time of significant climate changes demands active search for energy efficient structural systems with as low CO_2 emissions as possible in the phases of object construction, its exploitation, and its decomposition. As a natural raw material requiring minimal energy input into the process of becoming construction material, timber shows indisputable environmental excellence with very low CO_2 emissions. Therefore, the prefabricated timber buildings are suitable for building the energy saving objects of different standards.

The use of glazing in buildings has always contributed to openness, visual comfort, and better daylight situation. Although characterized by weak thermal properties in the past, glass has been gaining an ever-greater significance as a building material due to its improved thermal, optical and strength properties, resulting from years of development. Manufacturers have improved thermal insulation and strength of the glass over years [7] and the factor of energy transmission of solar radiation which enabled not only the internal illumination of the building with big glass surfaces, primarily oriented toward the south, but also the solar energy heating.

Nowadays, timber construction combined with the usage of suitable and properly oriented glass surfaces represents a huge potential in residential and public building construction. The fact that location of Slovenia on the southern side of the Alpine range enables considerably high portion of the solar potential in the time of heating season results in high portions of solar gains with the proper installation of bigger glass surfaces in the southern side of the building envelope [8-10]. Consequently, so-called timber-glass buildings have been developed in order to provide the highest possible solar potential and internal natural illumination. In that way, fixed glass surfaces are installed besides windows primary in the southern part of the building envelope (Fig. 1). Such wall elements were earlier not considered as load - bearing to horizontal loads because of the extremely brittle behaviour of the glass. Only conventional prefabricated frame-panel wall elements with classical OSB or fibre-plaster boards were mostly installed on other three sides of the building envelope.

However, it is important to emphasize that consecutive asymmetrical installation of load-bearing wall elements of the building envelope, if timber-glass elements are considered as completely non load bearing, leads to the phenomenon of torsion in single floors due to the seismic load. As schematically presented in Fig. 2, the position of the mass floor centre (M) in such case can significantly deviate from the centre of stiffness (R) of the load-bearing elements.

Namely, the possible phenomenon in the mentioned case can be the so-called soft floor, which should be avoided when designing multi-storey buildings in seismic areas [11]. This phenomenon can be constructionally solved in two known and in engineering practice common used methods:

- Inner conventional prefabricated frame-panel wall elements can be additionally installed; however, this is not in line with contemporary architecture of residential buildings aiming to enlarge natural illumination and general living comfort.
- Special additional load-bearing diagonal elements can be installed in timber-glass wall elements of the building envelope, which are evidently visible (Fig. 3). Still, this practice is mostly used in public buildings only.

Subsequently, lots of researchers deal with the solution of the problem by means of load-bearing timber-glass wall elements. In this case, studies of non-linear seismic response of the buildings on object classes should be done, and accordingly such design methods should be developed that are reliable enough for introduction in construction. Importantly, the basic standard condition [12] – life safety should be met.

Fig. 1 Timber-glass houses with south-oriented fixed glazing

Fig. 2 Phenomenon of torsion on the floor due to deviation of mass (M), and centre of stiffness (R), randomly chosen case

Fig. 3 Detached house with fixed glazing with south-oriented and additionally installed visible diagonals; designed and photographed by Architekturbüro Reinberg ZT GmbH Vienna

The timber-glass wall elements are formed as alternative load-bearing members on horizontal weight which can significantly contribute to additional horizontal load-bearing capacity and stiffness of the whole building. Moreover, they reduce the torsion impact on single floors and at the same time the installation of the visible diagonals can be avoided. This requires the failure not to run at the glass panel, which is as a very un-ductile structural element, but on the joint surface between the glass and timber frame or on the steel corner joint inter-storey elements which can ensure high level of ductility of such load-bearing wall elements. An interesting alternative method of the development of timber-glass wall panels without any adhesive is shown in [13]. In [14] innovative hybrid structural components composed of cross-laminated timber frame and laminated glass infill without using any adhesive to examine their response on the reverse-cyclic loading. As a result, in the case of specimens with low vertical load, the strength degradation demonstrated on average twice higher than in the cases of specimens with high vertical load. The stiffness degradation was not influenced either by the intensity of vertical load or by the number of glazing panels. Therefore, it was possible to formulate this phenomenon with a common equation, which is important for the development of future mathematical model of the tested type of structural components.

The goal of the study analysis in this contribution aims to find a solution to change a conventional board (plaster-fibre, OSB) of framed-panel wall elements with fixed thermal-insolation glazing. Importantly, by the right procedure of connection details in the connecting plane of the timber-glass frames, these can be considered as additional load-bearing vertical elements on known horizontal strain with proper level of ductility. This is briefly presented in the form of experimental study in Section 3. So-called timber-glass wall elements were developed and experimentally analysed in detail on numerous specimens in the frame of international research project WoodWisdom LBTGC [15]. However, it has to be emphasized that the costs of such experiments are too high to be recognized as useful in engineering practice using also various types of un-tested walls and box-house models. There are also many various parameters, such the adhesive and glass type and thickness, the bonding connection type, etc., which significantly affect racking stiffness of timber-glass wall elements and have to be very carefully analysed, [15-18]. On the other case, the group of authors widely investigated a case where the glass panes were completely not bonded to the timber frame, [19, 14].

Therefore, the second part in Section 4 as the main and final goal of the presented study, a quite simple mathematical model of the box-house prototypes is developed using a fictive diagonal element for simulating the racking stiffness of the bracing timber-glass wall element. It enables designers its application in a quite simple calculaculation software in order to determine the horizontal load-bearing capacity and stiffness of such timber-glass wall element and further also the calculation of oscillating form of the whole timber-glass building model. Such mathematical model can be later used for determination of complete seismic response of such buildings. A simple example performed on previously experimental box-house model is presented at the end of the study. However, the behaviour factor (q) should be determined first in that case. Only then such design methods can be finally developed that are reliable enough to be introduced in common engineering practice for a complete seismic calculation analysis of such timber-glass structures.

However, it should be especially finally emphasized that these topics are not yet included in European standards such as [11] or [12], since they are the first such implementing European guidelines in terms of glass construction as support and implementation of existing Eurocodes [20]. Nevertheless, studies are already mentioned in these guidelines which explicitly state that they are still in the stage of an academic level only. Generally, each object is unique, so a designer should provide sufficiently high resistance to all expected load cases, as determined by European standard. All presented and developed timber-glass wall elements from our article, separately listed in [20], can only increase this kind of calculated loads on request and at suitable constructor knowledge who does not need to use only known load-bearing wall elements or other strengthening methods (e. g. diagonals) in order to ensure sufficiently high resistance to expected horizontal loads (wind, earthquake), which are not the topics of this study. Hereby the problem of the so-called soft floor can be avoided, and all parameters of modern energy efficient prefabricated timber building can also be taken into consideration.

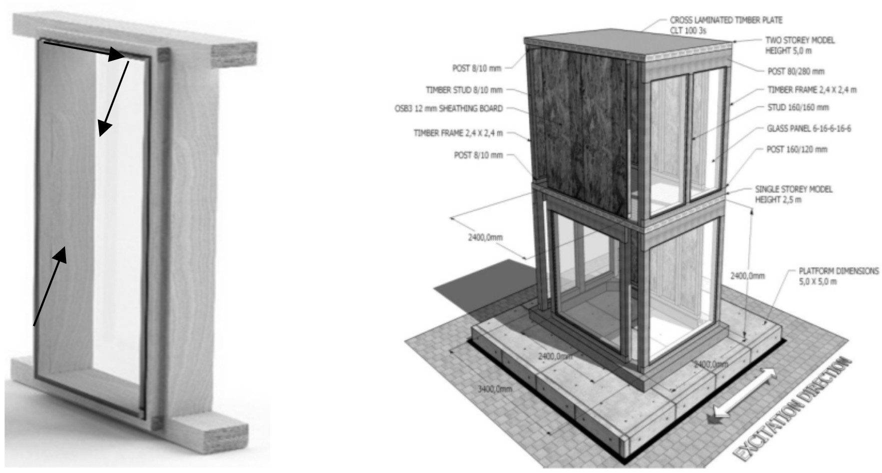
2. Materials and methods

Prefabricated framed-panel wall elements are made of timber frames composed by studs and longitudinal posts and sheathing boards (fibre-plaster or OSB), which may be unilateral or bilateral with nails or staples attached to the timber frame. The soft thermal insulation is installed in the space between the frame structure which together with outer stiff thermal insulation provides sufficient thermal insulation of the outer wall elements. Such prefabricated elements were in their original form technologically manufactured only as single-panel elements (Fig. 4a) with the standard length 1250 mm which was the standard length of sheathing boards. In 1990s, the single-panel system became a macro-panel system (Fig. 4b) for technological requirements after faster manufacture, so the entire wall systems were manufactured in one piece of 12500 mm length with mostly built-in window and doors openings. In terms of horizontal loads, a macro-panel system is statically considered as the sum of separate single panel wall elements. However, the method A in Eurocode 5 [12] requires only the consideration for the contribution of the single-panel elements without any window and doors openings.

a) b)

Fig. 4 a) Single-panel, and b) macro-panel wall system

Several studies [21-24] in the known literature prove that elements with window and doors openings can contribute to a certain extend to horizontal load-bearing capacity and stiffness of such wall elements. Therefore, timber-glass elements, where conventional sheathing is replaced by insulation glazing (Fig. 5a), can be considered as load-bearing to horizontal loads to a certain extend. Obviously, horizontal force transfer should be assured both over connecting plane glass-timber with the help of the suitable adhesive and over fictive tensile diagonal of the glass panel, as schematically shown in Fig. 5a [25-27]. Furthermore, it should be emphasized that such load-bearing timber-glass wall elements should be then incorporated in a load-bearing wall system of prefabricated frame-panel macro-wall systems and used in the models of timber-glass prefabricated objects, presented in the shape of the simplified *box-house* models in Fig. 5b, which were experimentally tested in the frame of the project [15] on the shaking table of IZIIS in Skopje [28].



a) b)

Fig. 5 a) Type single panel wall element with fixed glazing and schematic presentation of horizontal load transfer, b) *Box-house* model of a timber glass building

3. Results and discussion

3.1 Experimental analysis

Experimental analysis of timber-glass wall elements

Prefabricated single frame panel wall elements with fixed three-layered insulation glazing panel were first tested for monotonous static load according to the standard EN 594:2011, [29]. The vertical static load was constant and scaled up to 25 kN/m. The tests were then resumed with cyclic horizontal point load under the same load. In addition, the Niedermaier *end-joint* type 1 [30] was used to provide the joint between glass panel and timber frame. Two-component polyurethane adhesive of 5mm thickness and the annealed glass of 3x6 mm thickness were used, and the space between glazing was 16 mm thick. Two types of specimens were tested; they are schematically shown in Fig. 6:

- wall elements with insulating glass unit (IGU) in one piece (TGWE-1),
- wall elements of equal dimensions with a glass panel in two pieces (TGWE-2).

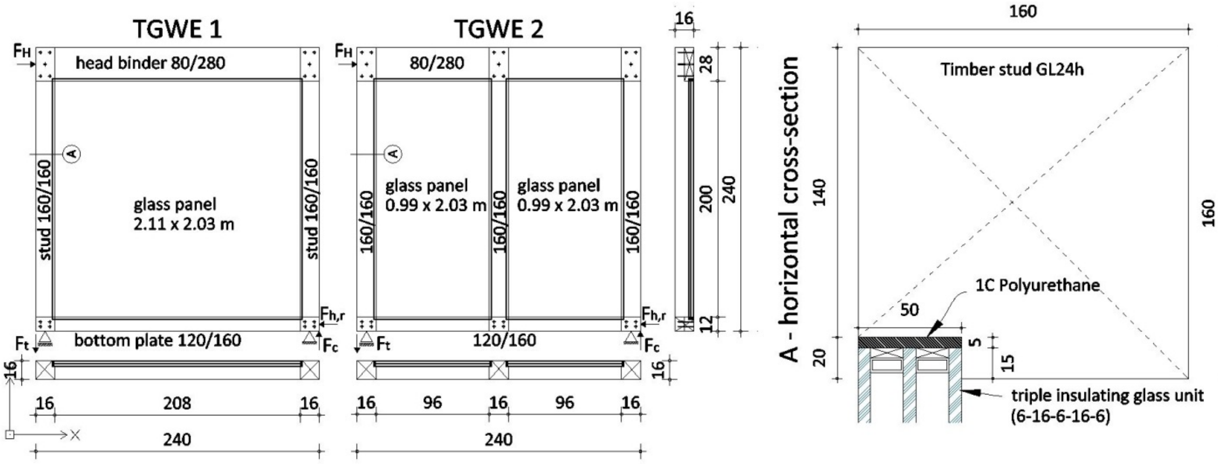


Fig. 6 Geometry of tested timber-glass wall specimens

The results for all obtained hysteresis of cyclic tests for both types of all tested specimens with drawn first envelopes of hysteresis curves are shown in Fig. 7.

It can be observed that the test samples with glazing in one piece (TGWE-1) notably prove slightly higher horizontal load-bearing capacity and especially higher stiffness. However, hysteresis curves show that the ductility for TGWE-1 is significantly lower, which could significantly influence on seismic resistance of such type of load-bearing timber-glass wall elements. The average ductility calculated according to EN 12512 [31] amounts for d = 2.8 for TGWE-1 and d = 3.1 for TGWE-2. The detailed presentation of the results under static horizontal load, calculated values for horizontal stiffness and detailed analysis of measured values with additional recommendations for practical usage can be found in detail in [15] and [28].

The reduction in load capacity in repetitive cycles is presented in Figure 8, where the force-displacement diagram shows the envelopes of the first, second and third cycles for all tested samples. The curves are markedly antisymmetric, and a cyclic decrease in stiffness is also observed. Additionally, the calculated mean values of the racking stiffness with the stiffness reduction chart for the first three envelopes are also presented for TGWE-1 and TGWE-2 test samples.

The stiffness diagram in Fig. 8 shows a slightly larger decrease in stiffness from the first to the second cycle for TGWE-2 type (16.3 %). From the second to the third cycle, the decrease in stiffness is more pronounced in the TGWE-1 type (8.6 %). The total decrease in stiffness, i.e., difference between the first and third cycle ranges from 19.1 % (TGWE-2) to 21.2 % (TGWE-1), respectively.

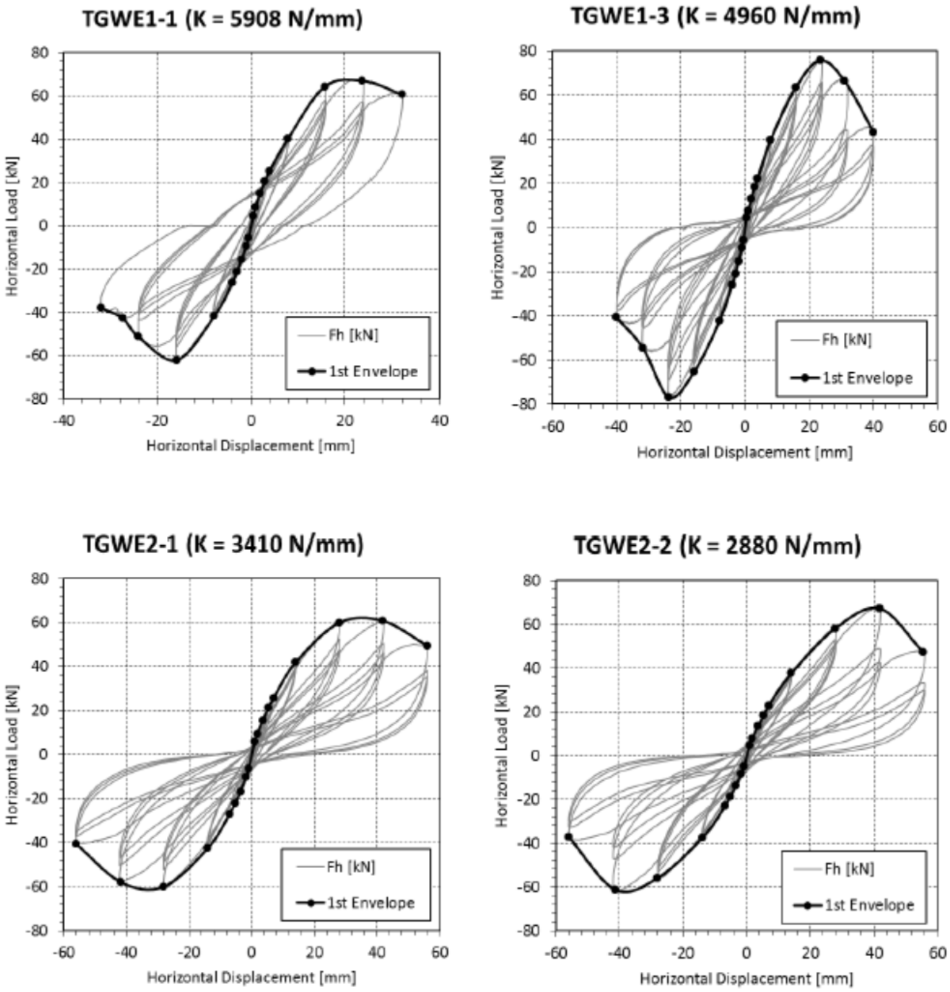


Fig. 7 Presentation of the response to horizontal cyclic load for both groups of specimens and calculated stiffness

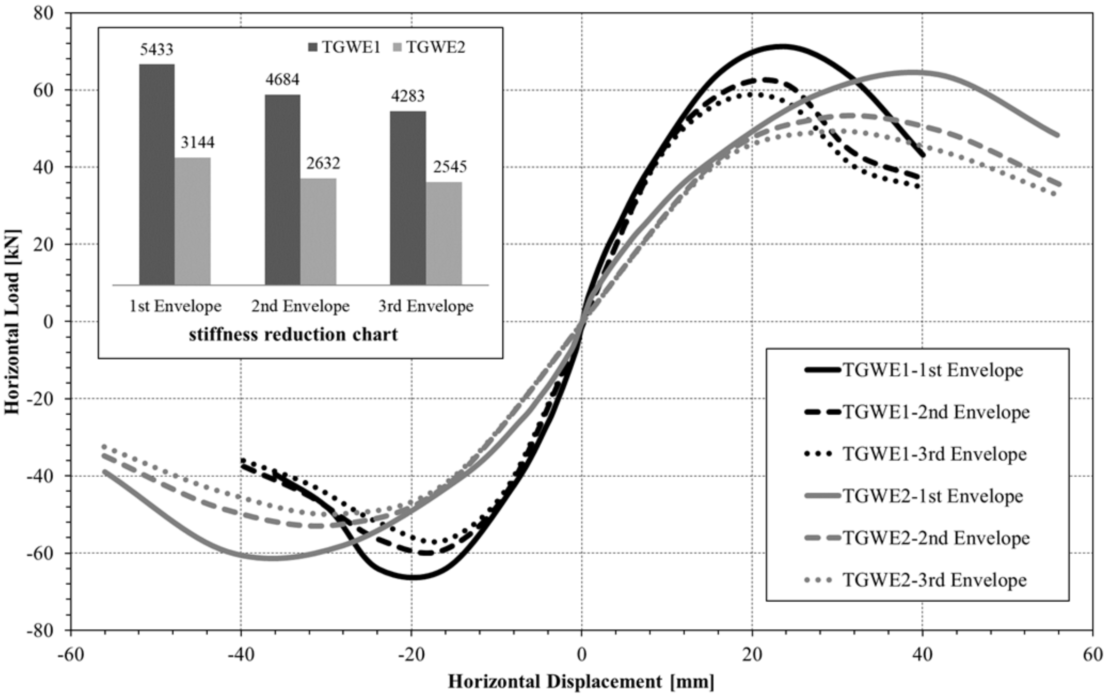


Fig. 8 Presentation of the response to horizontal cyclic load for both groups of specimens and calculated stiffness

Experimental analysis of box-house timber-glass specimens

The further analysis connects together the previously experimentally tested TGWE-1 and TGWE-2 timber-glass wall elements in different ways by conventional timber-framed wall elements sheathed with OSB (TFWE-1) boards. Consequently, as the final product so-called *box-house* timber-glass building models are developed, schematically presented in Figure 5b, and tested on the shaking table IZIIS in the Skopje institute. Single and two-storey composed *box-house* models with different settings of TGWE and TFWE wall elements are photographically presented in Figure 9. It should be mentioned that insulating three-layered glass panels from non-laminate glass were used just for the economic reasons, while laminate glass should be used in practice for safety reasons because it significantly increases the glass ductility. Anyway, failure mechanism should be created in order to generate the failure along ductile steel inter-storey hold-downs or at least along adhesive in connecting plane glass-timber, and by no means the failure along the glazing, which would lead to the instant brittle fracture.

Four single-storey and four two-storey objects with ground plan 2.4 × 3.4 m and height 2.5 and 5.0 m, were constructed from wall elements, type TGWE-1, TGWE-2 and TFWE-1. Three-layered cross glued panel of dimension 2.4 m × 3.4 m and thickness 100 mm served for the connection of wall elements. The additional mass of 1600 kg was applied to the panel which simulated the impact of its own weight and live load in the floor element. Due to the higher stiffness in shorter direction, the panel transferred the majority of vertical loads onto wall elements, installed perpendicularly to the direction of excitation. The wall elements that were seismically loaded in their planes received only a minor portion of vertical load. This is an important boundary condition which affects the behaviour of these wall elements. The wall elements were attached to the AB foundation with WKR-285 type of angle brackets and with additional M12 anchors along the length of the bottom sill. The ceiling panels were joint to the wall elements by self-tapping wood screws 8/180 mm on mutual distance of 150 mm. Upper and lower walls were joint together in corners by metal angle brackets and M12 screws. In addition, dynamic tests were divided into two basic modules: i) lower intensity testing without failure in the structure or in the so-called elastic state (together with all joints) and ii) higher intensity testing, where the ground acceleration was scaled up enough to cause failure in the structure.

After the structure was loaded with recorded *Petrovac* and *Landers* accelerograms, the structure did not exhibit visible damages. In order to intensify the response of the structure, randomly generated ground motion in frequency range 2.0 - 15 Hz and ground acceleration from 0.1 to 0.4 g was applied, as shown in Table 1.

Fig. 9 Photo of tested single- and two-storey *box-house* timber-glass models

Table 1 Protocol of GLS model loading

Low-intensity testing		High-intensity testing			
GLS1 - GLS4 and GLS6 - GLS9		GLS5		GLS10	
Modified Landers	0.15 g	modified Landers	0.50 g	modified Landers	0.50 g
Modified Landers	0.25 g	modified Landers	0.75 g	modified Landers	0.75 g
Petrovac	0.22 g	sine-beat 9.856 Hz	0.10 g	random 2-15 Hz	0.25 g
		sine-beat 9.856 Hz	0.50 g	random 2-15 Hz	0.35 g
		sine-beat 9.856 Hz	1.00 g		
		random 2-15 Hz	0.10 g		
		random 2-15 Hz	0.25 g		
		random 2-15 Hz	0.40 g		

Deformations can be noticed in the glue line between the glass panel and timber frame, shear drift and corner uplifting. Fig. 10 (left) shows the values of these deformations for the GLS5 model at random excitation (2.0-15 Hz) with acceleration 0.4 g. The vertical displacement of the corner was 1.0 mm, however, shear wall drift (1.9 mm) and deformations of the glue line in the size of 1.2 mm were also noticed.

The tests of structure excitation or the so-called *sweep tests* were carried out in the frequency area 1.0-32 Hz and the intensity acceleration 0.01 g. Based on these, vibration periods of the structure were calculated; this could serve also for the evaluation of the reduction level of the structural stiffness and damage levels. The measured values before and after high intensity excitation are graphically presented in Fig. 11.

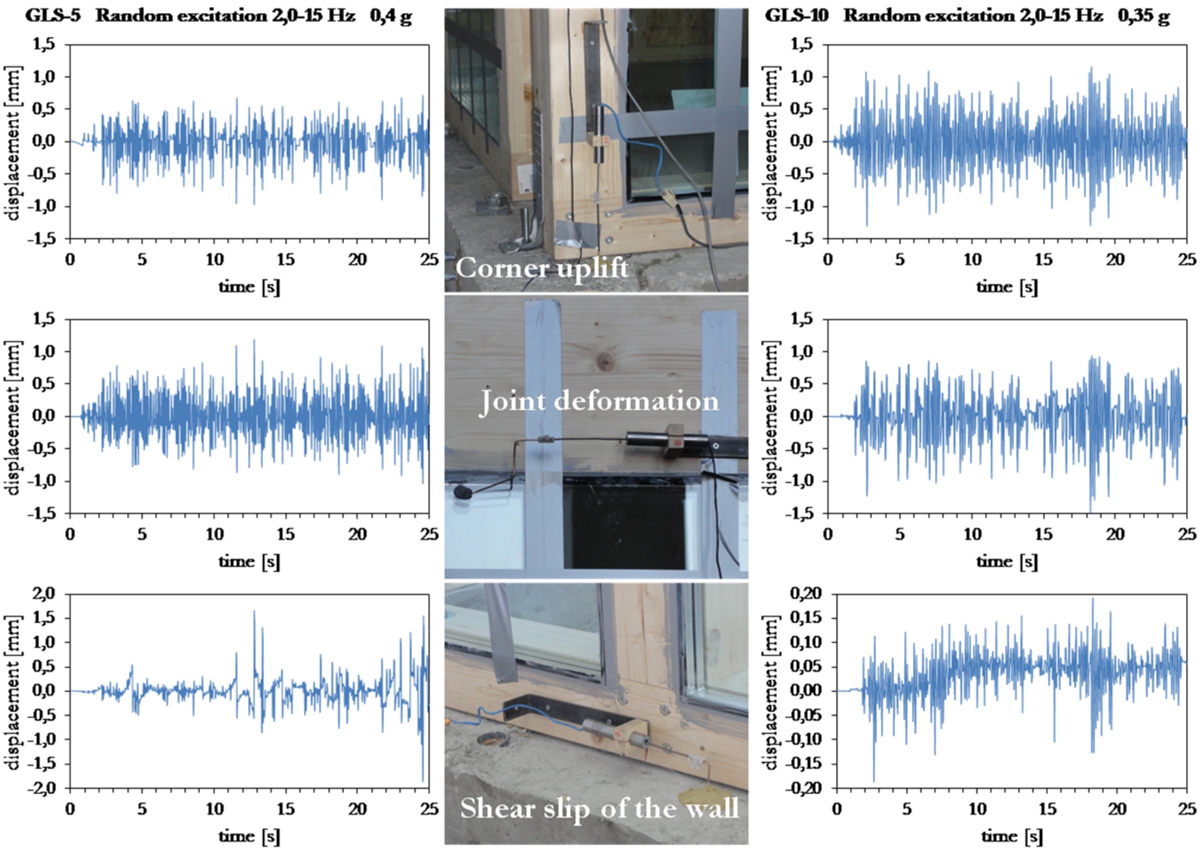
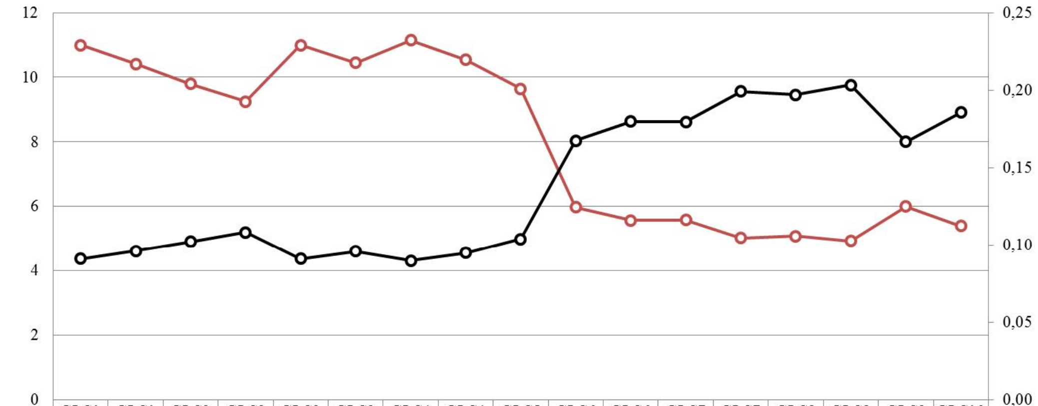


Fig. 10 Values of displacements and deformations of the GLS5 and GLS10 models for a high intensity dynamic test



	GLS1 before	GLS1 after	GLS2 before	GLS2 after	GLS3 before	GLS3 after	GLS4 before	GLS4 after	GLS5 after	GLS6 before	GLS6 after	GLS7 before	GLS7 after	GLS8 before	GLS8 after	GLS9 before	GLS10 after
1st frequency [Hz]	10,99	10,41	9,79	9,25	10,99	10,45	11,15	10,54	9,64	5,97	5,56	5,57	5,02	5,08	4,92	6,00	5,39
1st period [s]	0,09	0,10	0,10	0,11	0,09	0,10	0,09	0,09	0,10	0,17	0,18	0,18	0,20	0,20	0,20	0,17	0,19

Fig. 11 Measured values of basic vibration periods of the before and after high intensity testing

A detailed analysis of all results can be found in [15] and [28], however, it should be mentioned that the high intensity excitation did not result in any visible deformation in glazing, yet ductile failure mechanism with yielding of steel hold-downs between floors, the so-called rocking mechanism was generated at all test specimens. The majority of seismic energy was absorbed in the steel corner fasteners which function as ductile protectors of wall elements. In fact, this was also one of the goals of this study. The measured values of vibration periods before and after excitation (Fig. 11) also prove that there was no significant decrease in structure stiffness. The slight increase in the measured 1st time periods can result only from the yielding process in steel corner fasteners.

3.2 Mathematical modelling and numerical analysis of the single and two-storey box-house model

First, in order to perform the numerical analysis, it was necessary to define a suitable mathematical model of the structure. For this purpose, the previously introduced mathematical model with a fictive diagonal for determination of the racking stiffness of timber-framed wall elements with classical OSB or fibre-plaster (FPB) sheathing material [32] was applied and further developed for the timber-glass wall elements stiffness simulation. Following the expressions presented in [32], the fictive diagonal diameter for classical sheathing boards (OSB or FPB) is determined in the way that horizontal displacement of the actual wall element is the same as a horizontal displacement of the simplified model with a fictive diagonal, as schematically presented in Fig. 12. Lastly, the fictive diagonal diameter (d_{fic}) is expressed in the final form of:

$$A_{d,fic} = \frac{k_p \cdot L_d}{E_D \cdot cos^2 \alpha} \tag{1a}$$

$$k_p = \frac{1}{D_p} = \left(\frac{H^3}{3 \cdot EI_{eff}} + \frac{H}{GA_s}\right)^{-1} \tag{1b}$$

$$d_{fic} = 2 \cdot \sqrt{\frac{A_{d,fic}}{\pi}} \tag{1c}$$

with E_D being the modulus of elasticity of the diagonal, $A_{d,fic}$ the fictive cross-section of the diagonal and L_d the length of the diagonal.

However, it is important to point out that the already developed mathematical model by [32] can be used only for sheets which are mechanically fastened to the timber frame by staples or nails. The effective stiffness EI_{eff} is namely calculated using the gamma-method following the Eurocode 5 [12] expressions.

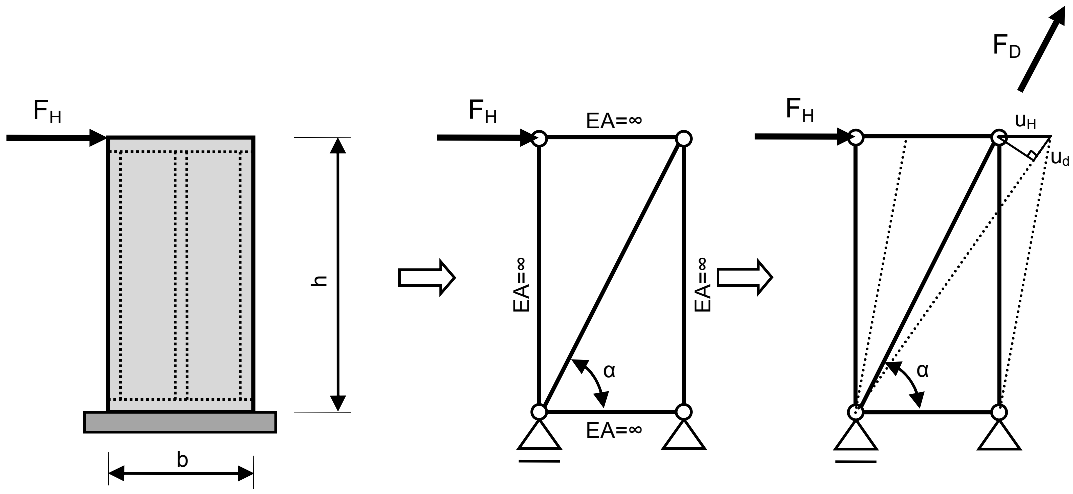


Fig. 12 Schematically presented transformation of a frame-panel wall modelled with truss members and a fictive diagonal

However, in case of timber-glass wall elements, where the glass pane is continuously bonded to the timber frame, it is not possible to determine the gamma coefficient and the effective stiffness EI_{eff} in Eq. 1b directly with the known expressions from the Eurocodes. Some already developed mathematical models with spring elements simulate the flexibility of the bonding line between the glass pane and the timber frame [25], followed by an extensive numerical parametric study [27], albeit the calculation time is too long to be implemented into the whole box-house building model. Therefore, for timber-glass wall elements the diameter of the fictive diagonal d_{fic} can be determined using experimental results from Subsection 3.1 upon derived equation only:

$$d_{fic} = \sqrt{\frac{4 \cdot F_{cr} \cdot L_d}{w_{cr} \cdot \ (\cos a)^2 \cdot \pi \cdot E_D}} \tag{2}$$

where F_{cr} represents the force upon appearance of the first crack and w_{cr} represents the corresponding displacement upon appearance of the first crack. The values for F_{cr} and w_{cr} can be determined only according to experimental testing.

The diameters of the diagonals were calculated in this way for each type of wall panel. As the box-house model is composed as a combination of classical timber-framed wall elements with OSB sheathing boards (TFWE-1) and the timber-glass wall elements (TGWE-1 and TGWE-2), the diameter of the substitutional fictive diagonal is determined for the OSB wall elements in semi-analytical final expressions using Eq. 1 and for the timber-glass TGWE-1 and TGWE-2 wall elements from the experimental results using Eq. 2. The results for d_{fic} are presented in Table 2. According to the results presented in Table 2, the horizontal stiffness of TGWE-2 and conventional TFWE-1 wall panels are practically equal, the stiffness of the TGWE-1 does not differ much as well. It also means that stiffness centre (R) and mass centre (M) of the box-house model coincide relatively well. Basically, this was one of the goals of our study, because consecutive high torsion loads along the building floor can be avoided in the case of an earthquake. Steel with the elasticity module E = 210 GPa was considered as material for diagonals.

Table 2 The diameter of the fictive diagonal for different wall elements

Wall elements	R (N/mm)	$\boldsymbol{d_{fic}}$ (mm)
TGWE-1	6704	16.60
TGWE-2	3595	12.16
TFWE-1	3636	12.23

In the mathematical model of the box-house are considered as rigid. Also, the timber frame elements are considered as axially rigid in order to eliminate the frame flexibility and only the flexibility of the diagonals is taken into account [32]. However, they are already further developed in [33] an upgraded mathematical approach for classical timber-framed wall buildings by including different contributions to the stiffness of the timber-framed walls, such as floor bending flexibility and flexibility in all floor to walls connections, which are not included in this study.

The mathematical model defined by this method was then used for the numerical analysis of the single-storey GLS5 and two-storey model GLS10. The numerical analyses were performed using the structural analysis software SAP 2000 v.17. Timber columns were modelled as axially rigid, while the timber cross-glued floor panels were considered as isotropic thin slabs ~~board~~. The floor slabs were subjected to a surface load of 2.0 kN/m^2. Fig. 13 shows the numerical models of the one-storey and the two-storey box-house using the fictive diagonals, while Table 3 presents the calculated fundamental vibration periods for both models and comparison with the measured fundamental periods as obtained from the experimental analysis (see Subsection titled *Experimental analysis of box-house timber-glass specimens*).

Table 3 shows that the results of the numerical analysis coincide well with the measured ones. Minor differences can be observed due to the fact that rigid supports were used in numerical models, while anchor elements in the experimental models have a certain flexibility which gives rise to a higher deformability of the structure and consequently slightly longer vibration periods. Subsequently, with the application of the developed mathematical models time-history analyses can be further performed using the Landers accelerogram, Fig. 13. The calculated horizontal displacements of the top of the structures as a function of time are shown in Fig. 14 for the single-storey models GLS5 and two-storey GLS10, respectively. The maximal horizontal displacement amounted to 2.67 mm for the model GLS5 and 11.86 mm for the model GLS10.

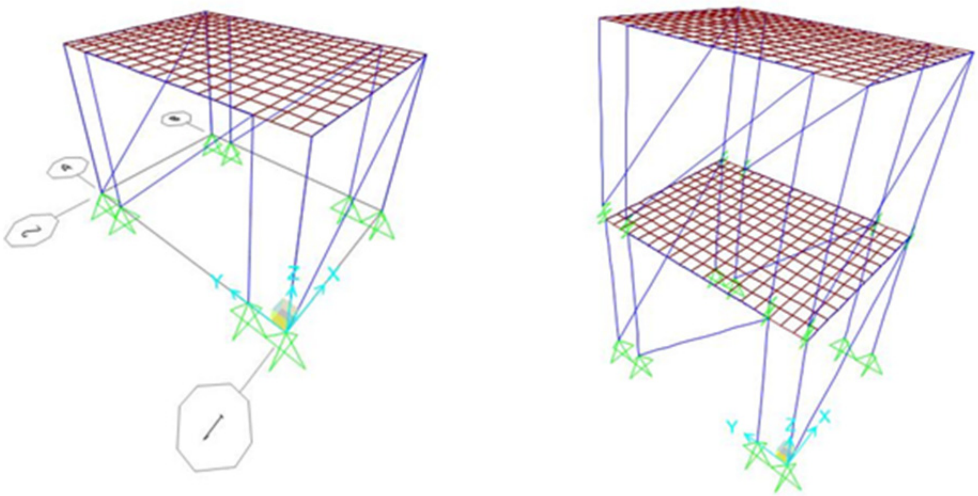


Fig. 13 Simplified numerical model of single-storey and two-storey model with a fictive diagonal (presentation of fundamental vibration forms)

Table 3 Review of fundamental vibration period of experimentally and numerically tested models

Model	Fundamental vibration period T_1 (s)	
	Experimental	Numerical
Single-storey GLS5	0.095	0.096
Two-storey GLS10	0.167	0.173

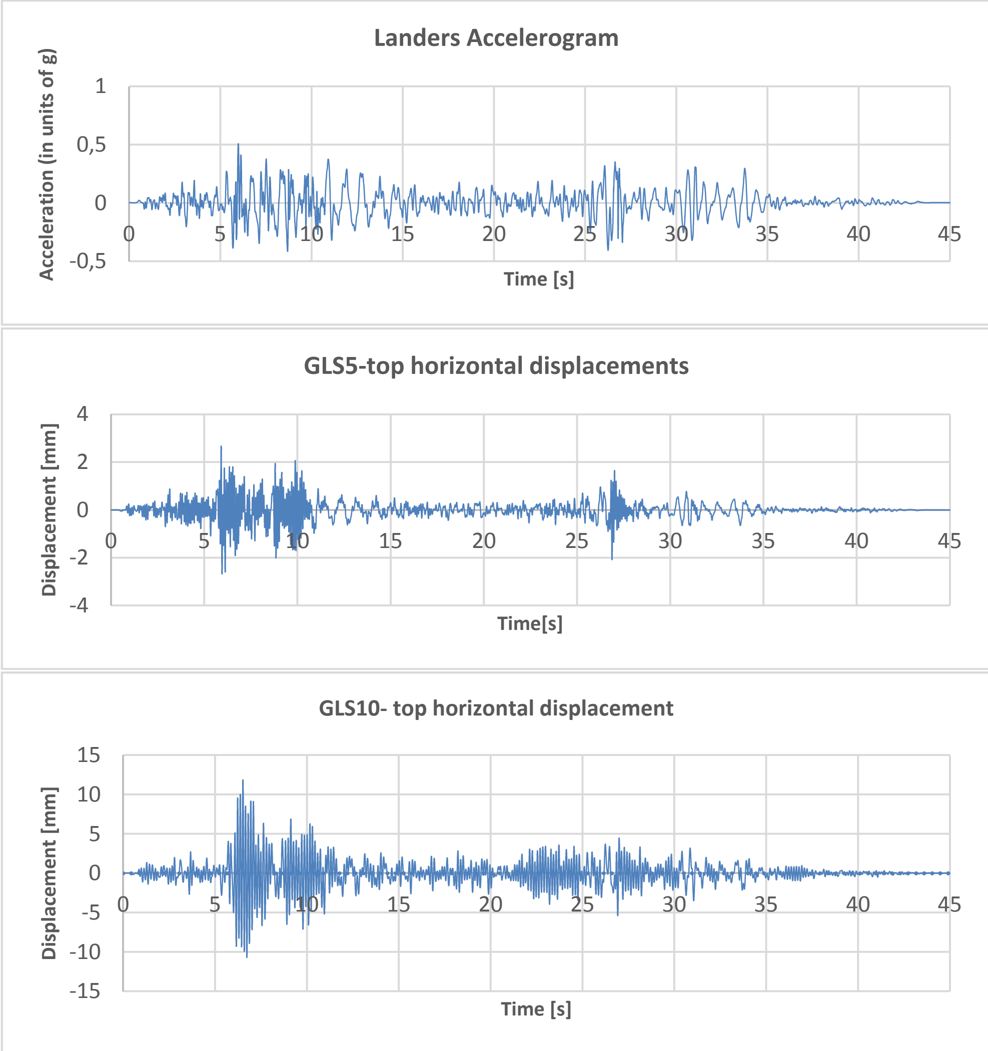


Fig. 14 Numerical values of the top horizontal displacements of the GLS5 and GLS10 models as the result of the time history analyses using the Landers accelerogram

4. Conclusion

The usage of enlarged portion of glass surfaces in modern timber objects provides solar thermal gains and impacts living comfort positively. However, large non-load-bearing glass surfaces under wind and seismic forces cause structural problems, above all in terms of uneven distribution of the horizontal force due to irregularity of the structure in its ground plan. Therefore, it is reasonable to ensure that such wall elements can provide certain horizontal load capacity and stiffness and also certain level of ductility in seismic active areas.

Firstly, discussed timber-glass elements were experimentally tested. Secondly, timber-glass wall elements were studied with combination of conventional frame wall elements which were used in the test box models of single-storey and two-storey objects. The timber-glass wall elements, used in the box models and subjected to highly intensive seismic impact showed sufficiently high level of robustness because the energy absorption was noted in uplifted and shear steel corner fasteners, whereas the wall panel remained in elastic area without any visible signs of deformation of the glue line. In Subsection 3.2, special mathematical models using fictive diagonal elements for prefabricated timber-glass wall elements are developed and upgraded from the already known study in [32], however, they are applicable for timber-framed wall elements with classical sheathing boards only. Consequently, previously experimentally developed load-bearing timber-glass wall elements with insulating three-layered glass pane are implemented into the linear seismic analysis of the whole timber-frame building by using a fictive diagonal approach for the first time in this study.

The developed new models for timber-glass elements however enable numerical simulation of seismic behaviour of single and two-storey timber-glass box-house models and demonstrated very good agreement with the previously experimentally measured results. Therefore, the models can be recommended for further parametric numerical academic studies analysing the influence of many various parameters.

Our further work will base on existing experimental results and expand numerical models in terms of actual nonlinear behaviour of single-wall and anchorage elements and determination of the factor for structural behaviour. Only then numerical analyses could simulate real structural behaviour as a whole and develop reliable design methods which could be introduced in practice. It is important to highlight once more that the basic requirement of the standard [11] should be fulfilled – that is life safety.

Finally, discussed timber-glass panels are in the development phase and at the level of implementing guidelines [20] in European standardization, even though some companies have started to use them in practice as additional panels after they were awarded international patent [34]. In fact, the usage of developed models should be implemented in practice after further seismic studies and proper certification of timber-glass wall element with CE marking.

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The implications of product modularisation on the development process, supplier integration and supply chain design in collaborative product development

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A B S T R A C T

Generating economies of scale is one of the most desirable goals when developing modular product systems. Since complex products are commonly developed in collaboration between an Original Equipment Manufacturer (OEM) and its suppliers, pursuing this goal inherently establishes interdependencies between the development process, supplier integration and supply chain design. To fully reap the benefits of modular product systems requires a comprehensive approach that encompasses these fields and addresses the interdependencies between them via a coherent collaboration between development and purchasing. This is the main focus of this work. In this paper, we first describe how the product development process has to be restructured for the concerted development of modules and overall products within the scope of a modular product system. Secondly, we propose a new collaboration model between the OEM and its suppliers, since OEMs need to collaborate directly with suppliers of lower levels of the value chain in order to facilitate the standardisation of components and modules across different products. Finally, we delineate an awarding process for both development services and production volumes for series supply that resolves the conflicting priorities of economies of scale and avoiding over-dependence on single suppliers. The process models described in this paper have been conceived based on systems engineering principles and have been successfully tested and further refined throughout several industrial projects carried out with two automotive manufacturers. The resulting approach will be demonstrated using a generic example taken from the automotive industry.

A R T I C L E I N F O

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1. Introduction

The importance of modular product architectures in reducing the complexity of the industrial realisation process of physical products is undisputed today and has already been described many times in literature [1, 2]. Yet, the existing literature mainly focuses on methodologies for the complexity-adequate design of modular product architectures. However, the introduction of a consistent modularisation strategy for complex products in cooperation with multiple suppliers and development partners has far-reaching implications for the organization of product development and procurement. First, the development process at the original equipment manufacturer (OEM) has to be restructured since there are now two different processes, which have to be aligned: (1) the development of modules to be integrated into different overall products and (2) the development of overall products. Both processes are temporally decoupled but must be coordinated with regards to their content. Second the effective standardisation of product components on different levels of the product architectures across different products requires the OEM to make design decisions and resolve technical conflicts within scopes of the technical system that he has previously managed as black boxes during the design process, because the first-tier supplier used to be responsible for it. In doing so, the OEM must collaborate intensively and directly with suppliers on lower levels of the supply chain during product development, that have previously been coordinated by first-tier suppliers. Therefore, a new collaboration model between the OEM and suppliers at the various stages of the supply chain is needed. And third, the awarding processes for external development and production services must be coordinated on multiple levels and across projects in order to achieve the objectives of modularisation while at the same time ensuring a robust design of the entire value chain that prevents the OEM from being overly dependent on single vendors. All the aforementioned aspects necessitate a coherent and strategically-aligned collaboration between development and purchasing, which so far has received scant attention in the research literature.

The purpose of this paper is to delineate the prerequisites for effectively tapping the potentials of product modularisation in the collaborative development of complex products. Thus, the paper provides three major contributions: (1) a process model for the concomitant development of modules and overall products, (2) a new collaboration model between the OEM and its suppliers that effectively supports the standardisation of product components and (3) a comprehensive process for awarding development services and production volumes which resolves the conflicting priorities of economies of scale and avoiding over-dependence on single suppliers.

The theoretical derivation of the proposed models and practices will be explained in detail in this paper. The empirical foundation of the approach is based on projects with two European automotive OEMs and five of their system suppliers (*development partners*) in which the authors had the opportunity to be involved as participants and consultants. Due to confidentiality agreements with all companies involved, neither the company names nor the detailed data can be presented here. We will therefore use a generic example from the context of the automotive industry to illustrate the developed approach as the result of our theoretical and empirical research.

The structure of the article is divided as follows: Section 2 outlines the basics of modular product architectures. Section 3 describes the specifics of the development process for the concomitant development of modules and overall products. Then, Section 4 will propose a new collaboration model between the OEM and its suppliers as part of these development processes. Finally, Section 5 will explain how to organize the awarding of development services and production volumes across various products with the objective of designing robust value chains based on modular product architectures. The article finishes in Section 6 with a conclusion.

2. Basics of modular product architectures

In order to understand the effect of modularity on the product architecture, it is necessary to take a close look at the defining principles of modularity from a systems engineering perspective. Modularity is a structural property of systems. A system is modular if it consists of subsystems whose inner relationships are much stronger than the relationships between these subsystems [3, 4]. This *primacy of the intramodular bond* leads to an *almost decomposable system* which consists of subsystems (modules) that are largely decoupled from each other [5-8]. Modularity can thus be seen as the opposite pole to complexity with regard to a system's structure. In other words, modularisation, meaning grouping technical components into modules that have strong internal relations but relatively weak external relations, is the most effective approach to reduce the complexity of a system. This process inevitably establishes a new system level of subsystems, which is why modularisation can be seen as a targeted hierarchization process from the perspective of general systems theory (Fig. 1). Applied to the concrete technical system of the product architecture which encompasses the product's components and the entire functional and physical relations between them, this means that a product architecture is modular if it consists of subsystems (modules) that are largely independent of each other with regards to both functional and physical relations. Functional relations encompass the flow of force, energy, material and signals between technical components. Physical relations refer to the physical separability of technical components and geometric structural dependencies between them. A comprehensive computer aided methodology for the systematic development of modular product architectures that considers technical aspects and customer needs as well as product strategy-related objectives can be found in [9].

All advantages (as well as disadvantages) of modular product architectures are a result of the module's relative independence in the product architecture. The lower strength of intermodular relationships not only helps to share development tasks, and thus simplifies system design, but also tends to increase product robustness by minimising *incidental interactions* [1] between modules. Optimally, the interactions between modules are limited to the energy, signal and information flow that is indispensable for fulfilling the desired function of the system. The central advantage of the modules being largely decoupled from each other is the possibility of concentrating the required variance and dynamics on specific modules and therefore limiting the effects of these external factors to the respective modules (Fig. 2). The required product variation can then be realized by simply varying the design of certain modules, whereas the design of the rest of the modules remains unchanged. The same principle applies for required product design changes over time due to a change of customer needs, new legal regulations or technological progress. In modular product architectures, these external dynamic factors can often be addressed by simply changing the design of certain modules, whereby as many other modules as possible remain stable, sometimes even over several product generations (*carry over*).

The extensive decoupling of the modules in the product architecture thus ultimately enables a far-reaching decoupling of the in-house product creation process from external competitive changes in the market, so that even in a competitive environment characterised by high complexity and dynamics, standardisation potentials in the product creation process and thus competitive advantages can be tapped (Fig. 3). In other words, a modular product architecture enables the generation of economies of scale [9, 10, 11] while at the same time providing a high variety of products as well as time-stable processes in the product creation process and simultaneously realising short product life cycles [12].

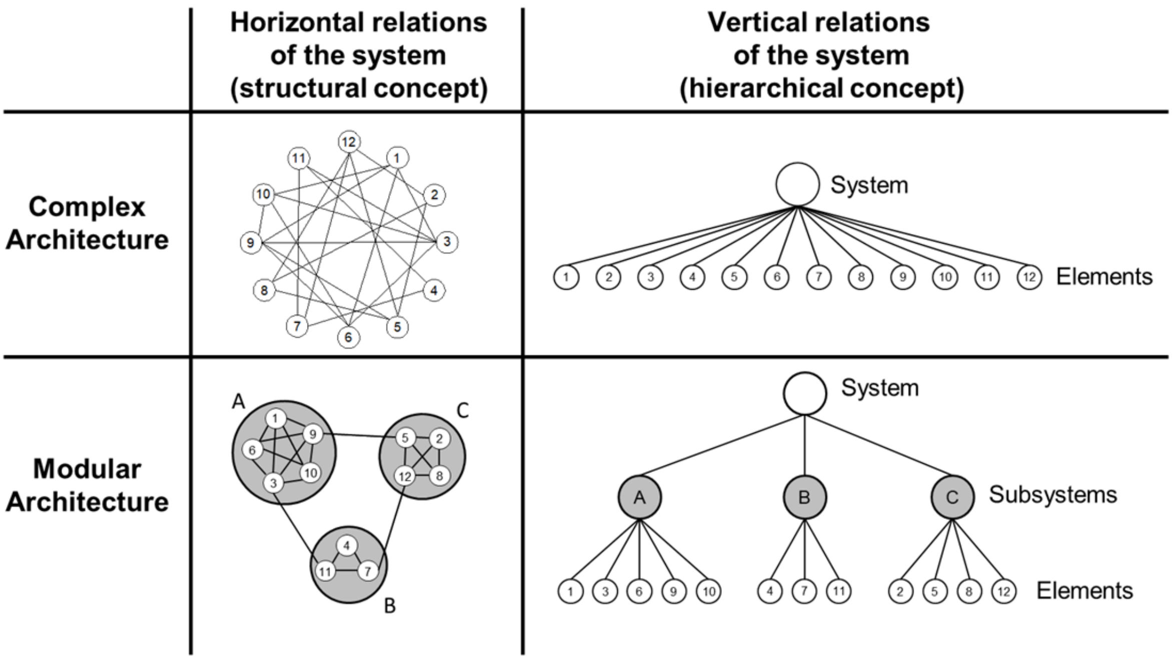

Fig. 1 Basic principle of modularisation from a general systems theory perspective

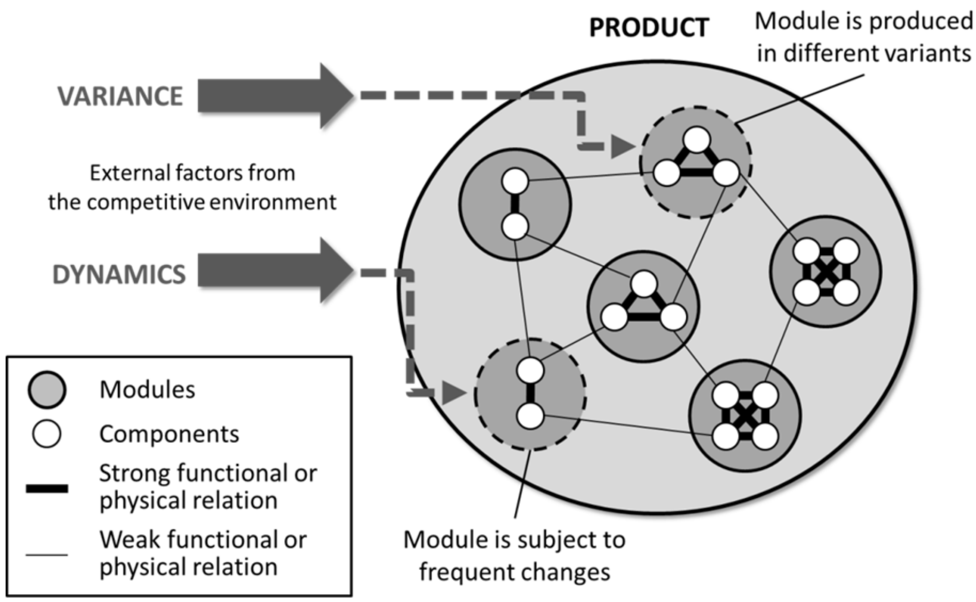

Fig. 2 Concentrating variety and dynamics in the product architecture

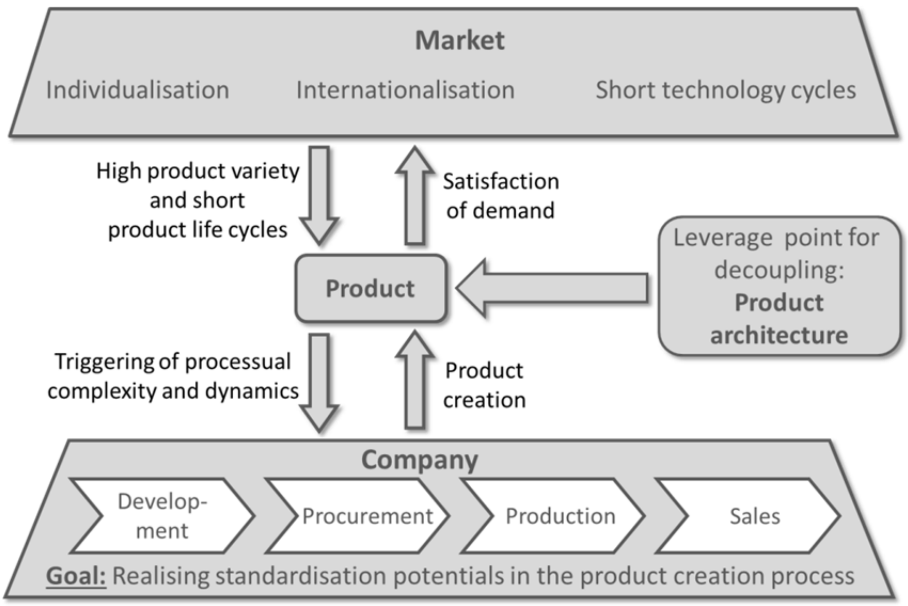

Fig. 3 The product architecture as the leverage point for the decoupling of external competitive changes and the in-house product creation process

3. The development processes of modules and overall products

The task of developing a product system based on a modular product architecture has a dual character: On the one hand, modules must be developed that can be used across different product variants and product lines and, in part, across product generations [12]. On the other hand, however, the resulting products should exhibit a high degree of technical integrity, meaning that the final products should appear to the customer as if they were *made of one piece* and should not be perceived as a motley compilation of separate components [13]. To successfully master this development task, its duality must be taken into account when designing the development process. In concrete terms, this means that separate processes should be defined for both module development and development of the overall products. Both development processes should be temporally decoupled so that the development and quality assurance of technical innovations within the modules do not have to be carried out on the critical path of the development project for an overall product [14]. However, they need to be coupled in terms of their content to ensure that the modules meet the requirements of the target products into which they are ultimately to be integrated. This alignment of module and product requirements in order to meet customer needs can be done by means of a strategic steering committee in which the areas of development, marketing, sales, production and purchasing are each represented with a high rank so that the different perspectives of these departments can be mapped onto the product. On the one hand, this steering committee can ensure that the requirements from the respective target products will be incorporated into the modules' development processes, but on the other hand this steering committee must also define binding specifications for the target products with regard to the modules to be used.

This planning process for the development of a modular product system is a very complex and time-consuming effort (Fig. 4). The technical requirements and boundary conditions of several target products must always be considered during module development. In this context, it is advantageous to define possible solution spaces so that joint intersections can be determined within the module development process and stepwise convergence towards uniform, discrete solutions can be promoted. Then again, the market interface and controlling must define a segment-compliant range of functions and quality levels as well as segment-compliant target costs. From this, among other things, the required variation and diversification of the modules can be derived in order to ensure a sufficient differentiation of the overall target products offered on the market. In both areas, technical and business planning of the modular product system, long-term aspects of strategic planning and innovation management have to be taken into account and competitive developments must be anticipated. For both, the modules and the overall products, innovation roadmaps have to be created which determine when which innovations will be incorporated into modules and products (for roadmaps, [15]). Since the modules to be developed can be used in several products that will be subsequently developed, greater effort in the upstream module development ultimately pays off. Due to the many influencing factors and the long prognosis period, such a strategic planning process is associated with considerable prognostic uncertainty. Therefore, an adaptation or further development process of the modules must be implemented, which runs parallel to the development process of the corresponding target products in order to make necessary adjustments of the modules with regard to volatile requirements of the target products.

The development of a completely new product that does not built upon a modular product architecture with pre-existing modules is usually preceded by a strategy phase, in which the product planning takes place. The result of this strategy phase is the *concept booklet*, a requirement document that defines the strategic positioning of the product to be developed. This document not only describes the competitive environment and the market segment the product is intended to enter, but also outlines important design specifications and first technical concepts on a high aggregation level. After completion of the product planning, the actual product development starts from scratch. Thus, very little prior knowledge about the development object exists, which significantly increases the uncertainty in early design decisions of the development project. As a consequence, over the course of the project, there is a considerable risk that technical problems occur, which had not been anticipated by the design team, requiring concept changes that might disrupt the original project schedule. Due to the lack of experience and empirical data, preventive quality and risk management as well as virtual and physical quality assurance during product development is correspondingly complex. A high degree of technical maturity cannot be reached before late stages of the project. Even at the product launch, quality problems often occur.

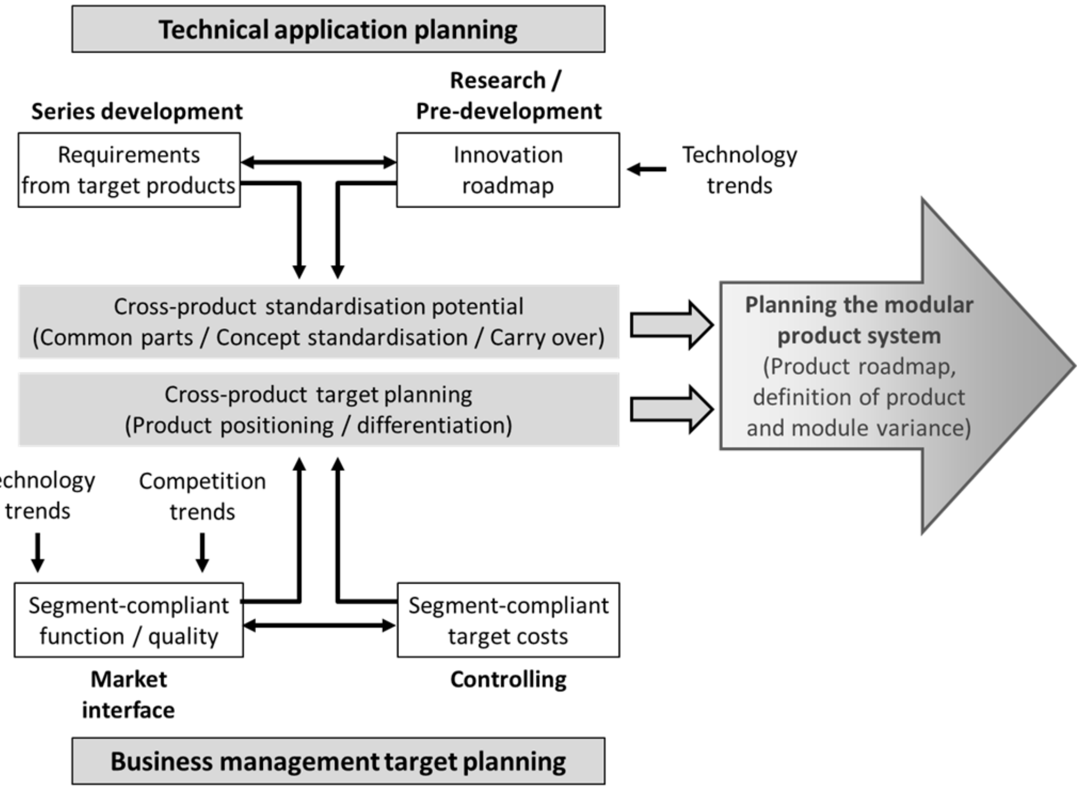

Fig. 4 Product planning process for a modular product system

The goal of the module development process in the context of modular product development, however, must be to provide modules that successfully passed complete quality assurance and for which a stable production process exists [14]. The development process for the target products then starts with a concept phase in which the responsible strategic project manager (*chief engineer* [14]) develops a product concept based on the existing modules. At the beginning of the concept phase, the chief engineer builds on already proven, or at least pre-tested, modules with a high level of technical maturity and functional reliability. This allows for reaching the proof of concept for the overall product in a relatively short time. After concept approval, the integration phase follows. This phase encompasses the product-specific adaptation and integration of the modules into a coherent overall product. The volume of the actual new development is limited to a few customisation components, which for example are required for the integration of modules at interfaces (e.g., specific holders etc.) or for the differentiation of the products with respect to visual appearance. The integration phase is ended by the design freeze before the marketability of the product is achieved in the assurance phase (Fig. 5). Throughout the development process, preventive quality and risk management can focus on the system integration of the modules and a limited number of changes within the modules. Even if a module's design has to be adapted for a specific product, the module's basic concept can usually remain stable, so that it is still possible to benefit from existing knowledge and experience.

The modular development process as described above can only be carried out successfully if the decoupling of the development processes of module and overall products is also reflected in the organisational structure of the company's development department. In such an organisational structure, there are development engineers and organisational units that have component responsibility for modules and work outside the critical path of the target products' development projects in the upstream module development, and others who have responsibility for overall products and carry out the integration and application development during the development projects of the target products. The different individual interests of these protagonists are determined in particular by the inherent contradiction between component-based standardisation and the aspired objective of high product differentiation. To prevent a conflicting *front* *line* between the involved stakeholders as well as to avoid unbalanced priorities, the responsibility for modules and overall products must be interlinked in a fractal manner across all hierarchical levels of the development organisation [16, 17]. Only such an organisational structure in development can efficiently support the standardisation of modules as well as the development of coherent overall products.

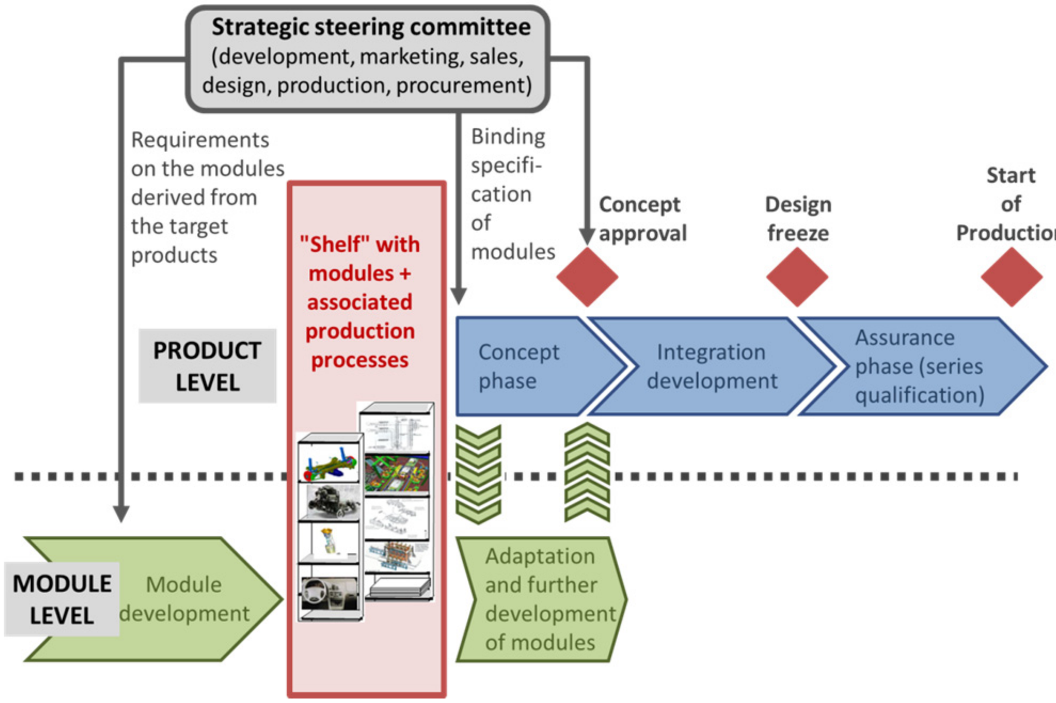

Fig. 5 Separation of module and product development process (modified according to [16])

4. Supplier integration in modular product development

Since the mid-1980s, the importance of outsourcing development services and joint development with external suppliers has been recognised as a significant factor in successful product development [18-25]. Especially in the automotive industry, the collaboration with development partners and the assignment of development tasks to them has often been the subject of scientific analysis [25, 26].

Until just a few years ago, a trend was observed among automotive companies to allocate steadily larger scopes of development to so called system suppliers in order to accelerate the development process and save human resources at the OEM [27]. The OEM increasingly viewed the outsourced technical systems as black boxes and controlled their development accordingly [28, 29]. In general, the development partners in this cooperation model were also the designated series suppliers and carried out both the system-technical integration of the procurement volume in development and the subsequent assembly integration on their own authority [30]. So, for example, the order for the development and series production of an automotive seating system was often completely assigned to a tier one supplier [31-32]. The respective tier one supplier carried out the actual development of the seating system based on the requirements laid down in the specifications. The development engineer responsible for the seating system at the OEM only guided and supervised the tier one supplier and mainly focussed on the integration of the seating system into the overall vehicle. The tier one supplier could assign the orders for the development and series production of modules and components within the seating system to subcontractors on its own behalf (Fig. 6). The main advantage of this collaboration model was that it allowed the OEM to control relatively large development scopes with only one development engineer, as the detailed design of the seating system and the coordination of the suppliers on the downstream levels of the supply chain was accomplished by the tier one supplier.

However, this outsourcing of actual development and awarding responsibility had two major downsides. (1) The development engineers at the OEM no longer had an in-depth understanding of the technical system for which they were responsible [28, 29, 33]. Since the definition of the manufacturing processes for the seating system and its components lay also in the hands of the tier one supplier, essential technical know-how flowed from the OEMs to the suppliers. (2) The OEM had no influence on determining which seating structure or which safety and comfort systems – such as airbags and seat belt buckles or seat heaters and seat ventilation systems – were integrated into the seating system. That prevented the OEM from standardising these technical components within the seating systems across different vehicles resulting in an uncontrolled increase in variety at the assembly and component level. This specific downside to the outsourcing of development services has been insufficiently reflected in the scientific discourse so far.

To effectively facilitate components' standardisation across different vehicles necessitates a new collaboration model between the OEM and its suppliers. Such a new collaboration model, however, must not entail a significant increase in capacity requirements in the OEM's development department. To address these aspects, the authors propose a new collaboration model, which will be illustrated in the following, again using the example of an automotive seating system's development.

As part of a comprehensive modularisation strategy, the OEM must regain control over the development of all major product components to be able to specify standard modules for different vehicles. This means that, in the course of module development, the OEM must again work directly together with the suppliers of the second and third level of the subsequent value chain and must again assume the responsibility for awarding the respective volumes. That way, it can for example be ensured that the same standardised seating structure is used in the seating systems of different vehicles to generate appropriate economies of scale. However, the specification of modules for certain technical systems implies the conceptual design of these systems. Thus, the OEM must again take over the responsibility for the system-technical integration of vehicle-specific procurement volumes during development. This is a prerequisite for deriving technical requirements for cross-vehicle module development. For reasons of capacity, this integration process is supported by an external development partner. This should usually be a potential tier one supplier or, in the late stage of development, the actual tier one supplier, because only they have the knowledge required for the system-technical integration of the procurement volumes (see also Section 5). This tier one supplier can also be a potential module supplier within the scope of the procurement volume for subsequent series production. The responsibility for development and awarding of the tier one supplier itself is limited only to vehicle-specific individualisation components of subordinate value (e.g., covers of a seating system).

However, this new collaboration model has the consequence that the development task at the OEM in part becomes more complex since the system-technical integration or *performance integration* [13], which was previously limited to a high level of aggregation (seating system-to-vehicle), must be extended to lower levels of the product architecture (e.g., module-to-seating system). As a result, the development engineer responsible for integration of the seating system has to acquire in-depth knowledge about the interaction of the modules and components within the seating system, which the developer previously managed as a black box during the design process. That means it is again increasingly important to gather *architectural knowledge* [34, cf. 35]. In addition, the development of the modules, which should be standardised across several vehicles, must again be controlled directly by a development engineer at the OEM responsible for components with regard to the requirements of the different target vehicles. In turn, this module developer must have an in-depth understanding of the internal structure and functionality of the individual modules, i.e. what is known as *component knowledge* [36, cf. 13, 37]. The solution of technical problems at the interface of different development and / or award volumes is now the responsibility of the OEM and requires a close functional coordination between the development engineer responsible for the system-technical integration and the module developers. This increases the OEM's coordination effort during product development (Fig. 7).

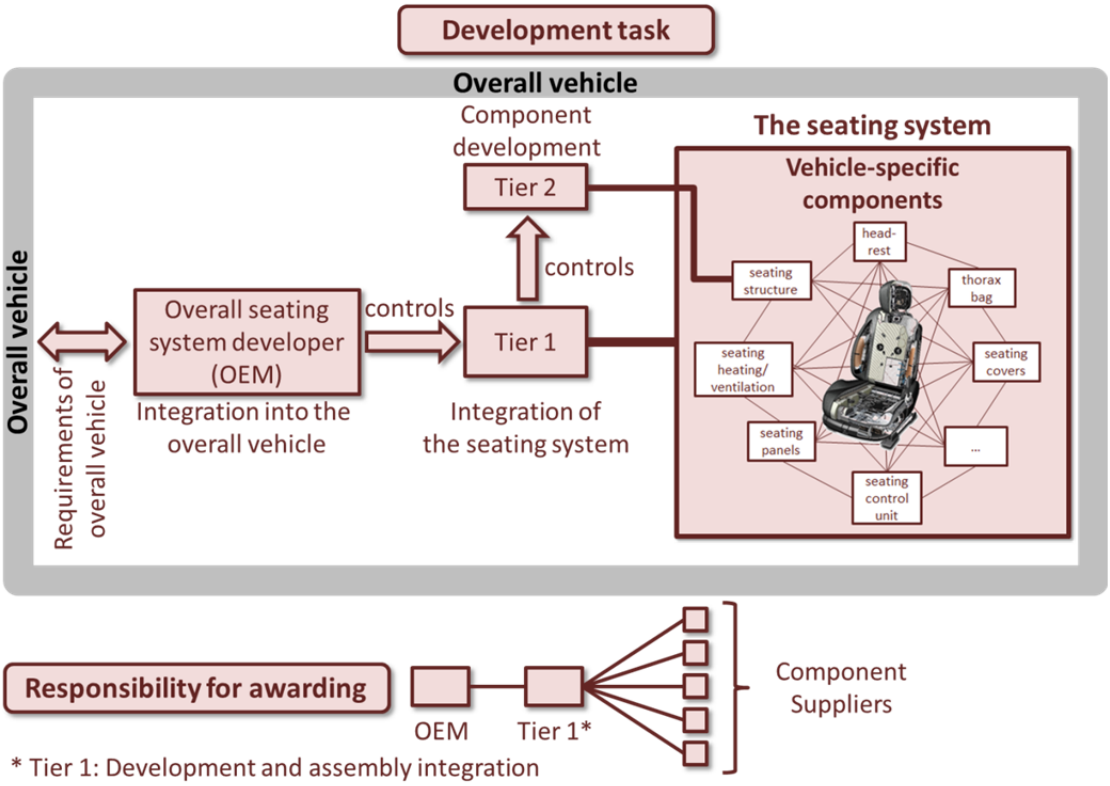

Fig. 6 Development task and responsibility for awarding **before** the introduction of a consistent modularisation strategy – using the example of an automotive seating system

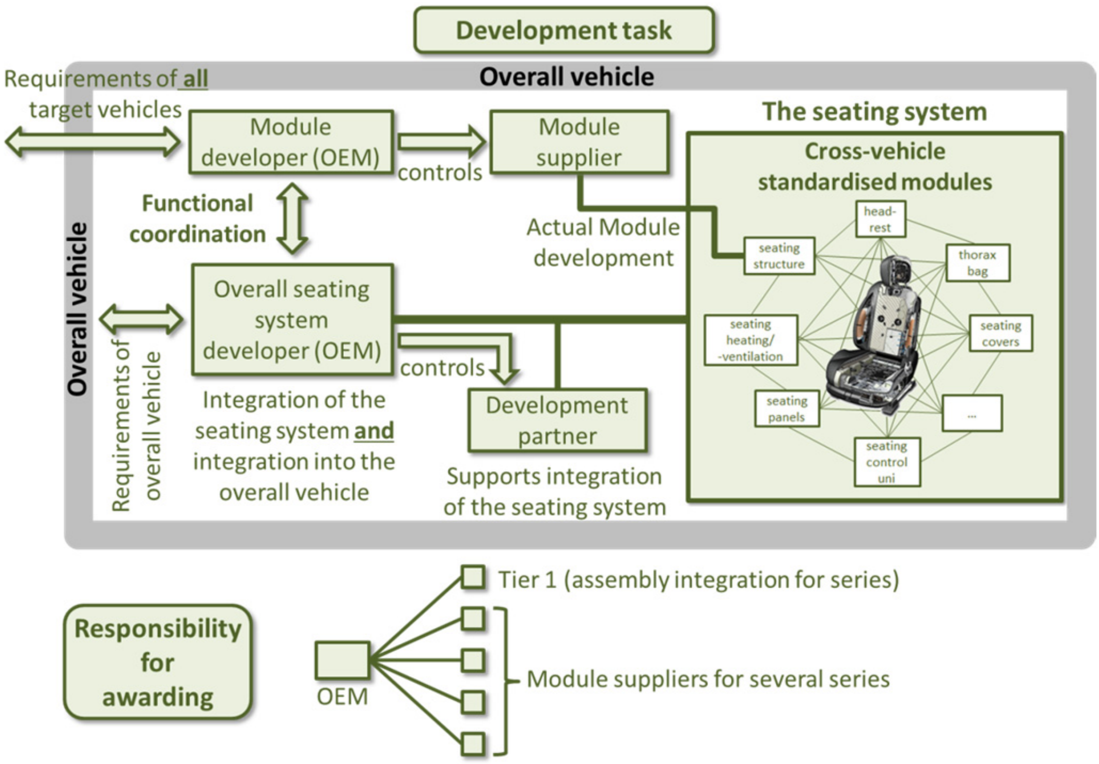

Fig. 7 Development task and responsibility for awarding **after** the introduction of a consistent modularisation strategy – using the example of an automotive seating system

This additional effort associated with product modularization has led some authors to rate the positive effects of modularization in product development as significantly less than originally hoped [13, 38, 39, 40], some even speak of the *unfulfilled promise of modularity* [13] in this context. However, there is a failure here to recognise that the implementation of a comprehensive modularisation strategy requires the coherent redesign of the development process, supplier integration and awarding process, as described in this paper, to fully reap the potential benefits of product modularisation. Under the premise of such a comprehensive approach, the extra development effort pays off, because it increases the overall performance of product development with great leverage by allowing for the development of a significantly larger number of different overall products with a very high degree of technical maturity in a relatively short time. Moreover, this additional effort in development at the OEM is not associated with an increase in capacity requirements in the OEM's development department: on the one hand, the development of modules used in different vehicles is more complex, but on the other hand, the number of modules to be developed decreases as a result of standardisation. Thus, the volume of vehicle-specific development projects, which now only involves integration and application development of technically mature modules, is significantly reduced. Therefore, it is often sufficient to shift internal development capacities from the vehicle-specific development projects to the module development projects. In addition, the actual development of the standardised modules continues to take place with the module suppliers and is only controlled by the OEM with regard to the requirements of the different target vehicles. As a result, the level of outsourcing of development services to external partners remains virtually unchanged overall. This also applies to the influence of external development partners in driving innovation. Due to the specific know-how of the suppliers (cf. *learning by doing* [13, cf. 35]), many module- or component-related innovation impulses will continue to originate from the suppliers (*push principle*). However, due to the increased knowledge of the OEM in terms of the interaction of the modules in the procurement volumes as well as the cross-vehicle-oriented control of module development by the responsible development engineers at the OEM, innovation ideas from the OEM to the suppliers are becoming more and more important (*pull principle*).

5. The awarding process

To design a robust value chain based on modular product architectures, the duality of the development processes described, i.e. the separation of module development and overall product development, must also be reflected in the awarding process. This means that differentiation between modules and integration volumes, which cover several modules, is necessary. The modified collaboration model with the development partner also requires a differentiation between the awarding of development services and subsequent delivery in series production. This will be explained below again using the example of the automotive industry.

5.1 The awarding of integration services in development and production

When the responsibility for system integration and awarding to downstream suppliers in the value chain was still with the tier one supplier, the OEM was forced to award the entire order for the development services and subsequent series delivery to a specific tier one contractor very early on, usually shortly after completion of the concept booklet. This was necessary to enable the tier one supplier to award the almost completely project-specific volume to the subcontractors of the downstream levels at an early stage in order to ensure the supply of parts in subsequent series production. Before the introduction of a comprehensive modularisation strategy, every vehicle generation was typically entirely new designed. Thus, prior knowledge about the concepts to be developed barely existed, so that design decisions had to be made under high prognostic uncertainty, in particular during early stages in product development. This uncertainty rendered design decisions less stable and led to frequent concept changes (cf. Section 3) resulting in high costs for change management and often even renegotiation of the series price. The bargaining power of the tier one supplier was relatively large due to the necessity of the OEM to bind early to a certain tier one supplier and the reduced knowledge of the OEM about the system integration within the procurement volumes. The only advantage for the OEM was that the development costs did not have to be paid directly, but could be allocated to the later series price.

If the OEM as part of the modularisation strategy again takes over the system-technical integration of larger procurement volumes and the modules for which the series production is awarded are already completely developed, the OEM is able to carry out a two-stage awarding process (Fig. 8). In the early phase of a vehicle project – in which it used to be necessary to award the entire production volume and thus to make far-reaching decisions with high prognostic uncertainty – initially only the engineering service for supporting the OEM in the system-technical integration of the respective procurement volume up to the design freeze is awarded. Hereby, the selected development partner is usually a potential tier one supplier. This is because only these suppliers have the required development competence (especially with regards to design for manufacturing and assembly) to support the OEM efficiently in the system-technical integration of large procurement volumes. The OEM then directly remunerates supplier development costs. At the time of the design freeze, when the design of the entire vehicle has been completed, a second invitation to tender is issued, in which the remaining quality assurance of the procurement volume and the actual production output in terms of assembly integration and series delivery is awarded.

Since the concepts have a high level of technical maturity due to the already predeveloped modules and the high volume of common concepts, modules and parts, the remaining development risk at the time of awarding the series production is relatively low, so that there is a high degree of prognostic certainty for the series award. Nevertheless, some communication losses and handover problems in development are to be expected, if this second invitation to tender results in a change of the supplier, meaning if the later series supplier is different from the previous development partner up to the design freeze. When awarding larger assembly volumes, such as a seating system or a cockpit module, the production and quality expertise of potential suppliers must be carefully assessed. In the automotive industry, for example, a segment-specific differentiation must be made. If, for example, a supplier has so far only had experience as a seating system supplier for vehicles from the lower segment, it should be closely reviewed if this specific supplier can meet the increased quality requirements of a higher vehicle segment. This also partly affects the awarding of development services in the early phase of vehicle development.

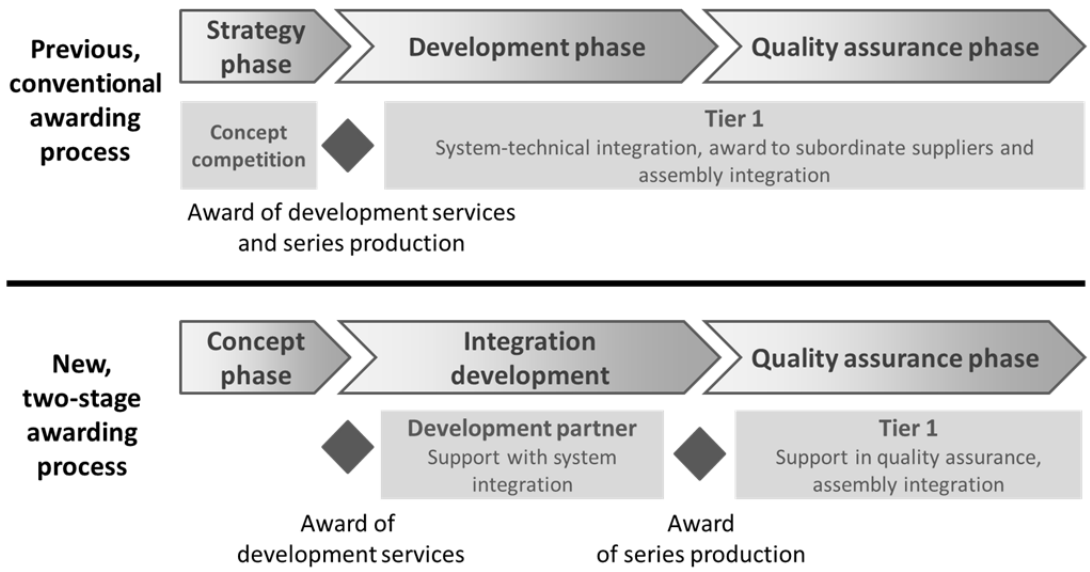

Fig. 8 Previous, conventional awarding process vs. new, two-stage awarding process

5.2 The awarding of modules

Since modules are used in several products and in part even in several product generations [12], and therefore are produced in large numbers over a long period of time, the awarding decision for the modules has a high relevance. This opens up a field of potential conflict for the OEM in assigning the modules in regard to the robust design of the value chain, which has so far attracted little attention in literature. To maximise the economies of scale, the OEM would have to bind itself exclusively to one supplier in the long term in order to obtain a high quantity of standardised modules over a long period of time. However, this would result in a high dependence of the OEM on this supplier and significantly reduce the robustness of the value chain as there would not be an adequate alternative in the event of supplier failure. Toyota's approach to address this issue is predicated on long-term, and sometimes exclusive, symbiotic collaborations with selected suppliers [14, 41] which is often assured via company shares. This approach cannot fully be applied to the structure of the western supplier industry. We propose a multi-stage awarding process for the modules to resolve the conflicting priorities of maximising economies of sales and avoiding over-dependence on certain suppliers. In contrast to the awarding of integration services in development and production, the dividing line for allocating the award volume does not run within the development process, but between different production volumes after completed development. The reasons for this and the specific design of this awarding process will be explained in more detail below.

As the functional relationships in modular product architectures are concentrated on the modules (cf. Section 2), the modules are usually also the primary technology carriers and thus often the starting point of innovations. For this reason, it is recommended that the awarding of modules be preceded by a concept competition that enables evaluation of the technology and development competence of potential suppliers. Due to the level of innovation and the large number of requirements to be taken into account from the different target products (cf. Section 3), the development of new modules is considerably costlier than later integration development. Therefore, the development effort and the development risk are accordingly high for the supplier. The quality assurance within the module development process is extremely complex and requires a close collaboration between OEM and supplier. In addition, the new development of modules involving technical innovations also touches on intellectual property issues. A division of the award volume, which is still done within development is therefore - in contrast to the integration development - not viable. The supplier can only be motivated to undertake the considerable development effort and to take on the development risk if, at the same time, later series production is also awarded to a significant extent. However, since the developed modules are then used in several products and product generations, the later volume of series delivery is so large that it opens up the possibility of dividing the award volume into different batches, which can then be awarded to different suppliers. The division of the batches should be staggered over time (e.g., depending on the planned vehicle launches) in order to be able to control the degree of capacity utilisation of the suppliers and also consider regional aspects (such as the supply of different production facilities) in order to reduce logistics costs and satisfy local content requirements. The supplier to whom the module volume was originally awarded develops the module and, at the same time, gets the award for the first, mostly very extensive, batch for series delivery so that the development effort pays off for this supplier (Fig. 9).

This supplier can also apply again when later batches are being awarded. However, the supplier already knows when the first batch of the production volume is awarded that the entire awarding volume will be distributed among several suppliers. Depending on the volume of the module, it may also be the case that the supplier who originally developed the module does not have the capacity to solely supply the global production volumes required by the OEM.

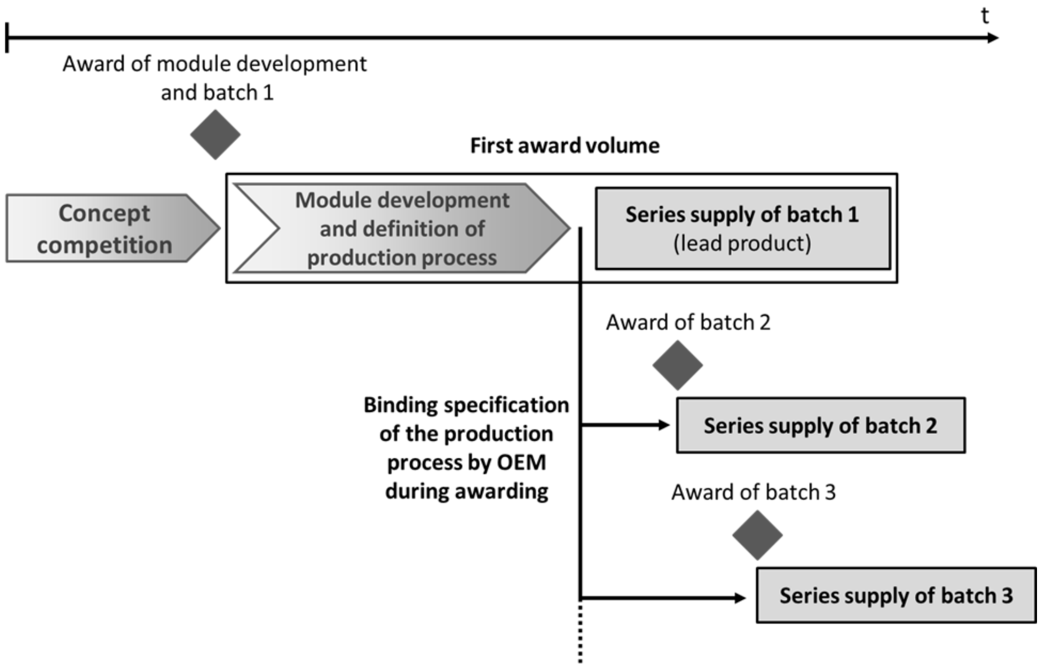

Fig. 9 Awarding process for modules

The division of award volumes in later series delivery requires strategic planning which must be anchored both institutionally and organisationally in the committee landscape of the OEM, e.g., in the form of a strategic award steering committee. The two most important representatives in this body, which must also include representatives from production logistics and quality management, are purchasing and development. Within this body, a strategic procurement roadmap must be developed which considers both the planned product launches and scheduling of technical innovations as well as the OEM's global procurement targets and the supplier's assessment in terms of their strategic direction, economic stability and their production capacity. The long-term planning of the awarding of modules thus requires a much more intensive coordination between development and purchasing than the procurement of purely project-specific volumes with a comparatively short-term planning horizon.

The example of Toyota [42-44] impressively demonstrates the importance of product design for manufacturing and assembly in the context of strategic quality management. Toyota sees itself primarily as a production company where development work allows for function, quality and efficiency, but these are actually realised in the factory. The design for manufacturing therefore has absolute priority in the Toyota development system. The joint development work with the suppliers provides for close and detailed coordination throughout the supplier network which aims to streamline the processes, synchronises the value streams and matches production systems along the entire value chain [14, 44-46].

Applied to the approach outlined in this section for the design of the module awarding process, this means that the OEM and the supplier to whom the development contract and the first batch for a module volume was awarded both share a common responsibility for design for manufacturing and the definition of an optimal production and assembly process. This process must then be specified with binding nature in subsequent awards for all other suppliers for this procurement volume. This requires that the production process is based on best-practice solutions that can be reliably implemented by every potential supplier. In order to ensure this, the OEM must again specifically acquire knowledge about the production and assembly processes of modules and integration volumes across several stages of the value chain. For certain key scopes of particular technical or monetary importance, this may also include a small pilot production and assembly line at the OEM. This facility has only a minor importance in terms of production volume and primarily fosters the development and continuous improvement of manufacturing and assembly processes. If this is not possible and the complexity of the awarded volume requires specific knowledge in terms of development and production which only one or a few suppliers have, then the acquisition of shares of suppliers following the Toyota model could be a conceivable alternative in individual cases for securing a long-term partnership. In this way, if necessary, exclusivity in cooperation can be ensured, which prevents the outflow of know-how through the development partner to potential competitors.

6. Conclusion

The individualisation of demand and the internationalisation of the geographical orientation of companies as well as shorter technology cycles have made the adequate handling of complexity and dynamics a decisive competitive factor in almost all industries [47]. The main question is how to reduce the complexity of product creation without restricting the range of products offered by companies. Modular product architectures, which serve as the basis for the development of modular product families, are of particular importance in this context as they enable the provision of a high number of variants and the realisation of short product life cycles while simultaneously opening up standardisation potentials in the product creation process.

In this paper we proposed a comprehensive approach to fully reap the benefits of modular product architectures in the collaborative development of complex products. This approach encompasses necessary changes to the design of the product development process and the awarding process as well as a new collaboration model for the integration of suppliers during product development.

Firstly, we have shown that the development of a modular product family requires a special design of the development processes which considers the dual character of the development task [16]. This duality exists in the development of standardised modules on the one hand, and sufficiently differentiated overall products of high coherence on the other hand. In order to meet both requirements, the module development process has to be temporally decoupled from the development process of the overall products. A strategic steering committee should be implemented that reflects the different product views of different functional departments and business units. This ensures that the modules meet the requirements of the target products.

Secondly, we proposed a new collaboration model with external development partners as part of the redesigned product development process. In order to achieve effective cross-product standardisation, the OEM must again control the development of all major product components to be able to specify standard modules to be used in different products. This forces the OEM to collaborate directly with the second and third tier suppliers in module development and take over responsibility for awarding modules within procurement batches. However, the specification of modules for certain technical systems implies the conceptual design of these systems. Thus, the OEM must again take over the responsibility for the system-technical integration of product-specific procurement volumes during development. As a result, the OEM must re-acquire specific knowledge regarding the function and structure of the modules and their interaction within the procurement volumes. Since the development of modules involves the consideration of requirements from several target products and the subsequent development of the overall products requires close coordination between the development engineers responsible for the module development and the development engineer responsible for the product-specific integration and application, the development task at the OEM becomes more complex overall.

Finally, we showed how to organise the awarding process, in order to generate economies of scale and, at the same time, ensure a robust design of the supply chain. With respect to the awarding process a distinction must be made between the award of development services and production volumes as well as between the module and integration volumes. The separation of the module and product development process allows for a two-stage awarding process in which initially only the development up to the design freeze and then later the remaining series assurance along with the production output, i.e. assembly integration, is awarded. In this way, more competition as well as cost transparency and security can be realised when awarding assembly integration in series production. When awarding the modules, there is a field of potential conflict between generating the greatest possible economies of scale and avoiding over-dependence on individual suppliers. This can only be resolved by dividing the entire procurement volume for the series delivery of several target products into different batches which will be awarded separately. Due to the complexity and level of innovation of module development, it is not possible to divide up the development scope. Since development costs and risks are accordingly high for the supplier, the first award of a module, in addition to the complete development order, typically must also contain the first production batch in series delivery with a correspondingly large scope.

With regard to current and future development, it can be said that complex products such as automobiles are increasingly becoming product service systems. In particular, the higher level of electronics and software (e.g., in-drive entertainment systems, driverless driving, car-to-car communication) hereby leads to new development processes and a reorganisation of production chains as well as to changed power relations between OEM and certain suppliers. In particular, the question arises as to who will *own* which customer data or who can use it. As a result, on the one hand, questions about the scope of outsourcing and the tailoring of modules must be posed again. On the other hand, however, the choice of individual product and process development partners and the design of development networks must also once again be questioned. An example is the purchase of the map service *here* by BMW, Mercedes and Audi for 2.8 billion euros in 2015, which in this context can also lead to challenges in the design of modules beyond OEM borders, which creates further need for future research.

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Exploring the link between project management approach and project success dimensions: A structural model approach

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ABSTRACT

Aligning the project management approach to a particular project is considered to be essential for project success. Based on the literature review, in this research, the project management approach is analyzed through differentiation between agile and traditional approaches within the specific managerial aspects. This research aimed to contrast these two project management approaches and explore their impact on different project success dimensions. The research was conducted on a sample of 227 project management professionals worldwide, using the PLS-SEM method. Research results denounced that, in most cases, the traditional approach is applied in project initiation and planning. It has proven to provide higher-level od project success, while, within all other managerial aspects considered in this research, they gravitate more towards the agile approach. By combining agile and traditional approaches, organizations can take advantage of some benefits of agile development without abandoning the stability provided by a traditional approach. The study is relevant for project management practitioners tailoring down the success-oriented project management approach and developing project management contingency theory for academics.

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1. Introduction

Contemporary challenges, dynamic, uncertain environments, and stakeholders increase project complexity [1]. There are many different, and in some cases, overlapping approaches to manage the complexities of any given project, make it difficult to determine which one is suitable to use to achieve project success [2]. Things get further complicated as the universal project success definition is still challenging to find as it is discordantly discussed in the literature. Despite extensive research in recent years, there has been little agreement on what causes project success and how. Many authors argue that aligning the project management approach to a particular project [2-4], particularly correctly matching the project characteristics [5], is essential for project success. In a current condition of rapid change and uncertainty, some authors considered that project success is determined by how project risks are managed [6]. Based on the literature review and relevant literature sources, in this research, a project management approach is analyzed through differentiation between agile and traditional approaches. The early adopters of agile believe that agile may positively affect project success [7-9]. Followers of a more traditional approach believe that agile is more chaotic and lacks the formal procedural rigor that the former possess [10], affecting project success. This raises questions about the value and effectiveness of different project management approaches and how they link with project success. There is a lack of research in this field, signaling a clear gap in the literature. This research aims to contrast these two project management approaches and explore their impact on different project success dimensions. The following research question is posed: How agile and traditional project management approaches differentiate concerning their impact on different project success dimensions within the project management process's specific managerial aspects? To answer this question, we empirically tested the relationship between the project management approach, applied within the specific managerial aspect, and individual project success dimensions. This was done on a sample of 227 project management professionals worldwide, using the PLS-SEM method. Such a course of action was taken due to this research's exploratory nature [11]. The research is relevant for project management practitioners tailoring down the success-oriented project management approach and developing project management contingency theory for academics.

The paper's remainder is structured as follows. Section 2 reviews the literature on project management approach and project success. Section 3 research model with research questions and hypotheses is given, while in Section 4 research method, sample, and data collection process are presented. In Section 5, statistical data and results are presented and discussed, followed by a conclusion with limitations and suggestions for further research.

2. Literature review

2.1 Project management approach

As global demands change, organizations move from a traditional, hierarchical management approach based upon command and control to an agile project management approach based upon collaboration, flexibility, and dynamism [12]. The traditional approach pursues a goal of logical sequencing that required deliverables to be set in advance and project development evaluated based on performance at a series of capabilities gated reviews [13]. As opposed to the traditional ones, agile management relies much more heavily on the training and skills of a collaborative cross-functional team to adapt the methodology to a problem that they are attempting to solve and to deliver projects piece by piece and make rapid adjustments as needed to speed up the phases of the project [14]. Bringing a project to a successful closing requires integrating numerous management variables such as planning, directing, team building, team communication, cost and schedule management, client involvement, requirements, change management, stakeholders management, etc. The multiple factors involved in management that are subject to changes in variables external to the organization and organizational management models cannot be a static or deterministic concept [15]. To differentiate the agile and traditional project management approach, according to different project variables, identified in the literature, the authors defined five groups: (1) project initiation and planning, (2) personnel management, (3) client involvement, (4) modularity of work and (5) troubleshooting. Each group describes a specific managerial aspect of the project management process. Project initiation and planning refer to how the project is initiated and planned – the level and complexity of upfront planning, clarity, and stability of project scope and requirements. Personnel management refers to the way how the project team collaborates, how work is organised, and what is the management style. Client involvement describes the importance and level of client involvement and commitment throughout the whole project, lifecycle. The modularity of work refers to the way how project work is done, describing the development process (the value of modularized and incremental work, sequence of iterations, prioritization). Troubleshooting refers to the way how changes in requirements are managed and implemented. Differences between the agile and traditional project management approach within the specific managerial aspects of the project management process, identified in the literature, are presented in Table 1.

Table 1 Agile vs. traditional approach in project management [13, 16-19]

	Variable	Agile	Traditional
Project initiation and planning	Scope	Largely emergent, rapid change; designed for current and foreseeable requirements	Known early, largely stable; designed for current requirements
	Project planning	Complex; iterative	Linear
	Contract	Based on time and resources based (variable-price)	Based on fixed prices, time, and scope
Personnel management	Team collaboration	Collaborative; agile	Plan oriented; less collaboration
	Team location	Distributed due to different physical locations	Co-located-all located at the same place
	Team organization	Self-organized and cross-functional teams; 100 % dedicated to the project	Strict separation of roles; access to external knowledge; pre-structured teams; spread across different projects
	Management style	Leadership and collaboration	Command and control
Client involvement	Client involvement and commitment	Dedicated, knowledgeable; co-located; representative, frequent collaboration	Minimal commitments; not co-located and not empowered
Modularity of work	Development model	Evolutionary-delivery model (iterative or adaptive models)	Linear or incremental (anticipatory)
	Fundamental assumption	Continuous design improvement and testing based on rapid feedback and change	Systems are fully specifiable, predictable, and are built through meticulous and extensive planning
	Quality control	Continuous control of requirements; design and solutions, continuous testing	Heavy planning and strict control; late heavy testing
	Prioritization	Client prioritized; time-boxed delivery	Manager negotiated; scope-based delivery
Troubleshooting	Requirements	Creative, innovative; requirements unclear; changes expected	Precise initial requirements; low change rate expected

2.2 Project success dimensions

There are various opinions on what composes project success and criteria by which the project should be judged. Still, no general agreement on project success has emerged appropriate for all projects [20, 21]. A specific project should focus on its explicit dimensions, and these dimensions should be determined according to the particular project type [22]. Traditional project success measures focused on the so-called iron triangle, completing the defined scope of work to specification, and meeting the time and budget goals [23]. Although this may seem right in some cases and suitable in the short run when time is critical, quite often, what appeared to be a troubled project, with extensive delays and overruns, turned out later to be a great business success [24].

Table 2 The five dimensions of project success [21]

Project success dimension	Measures	Time
Project efficiency	Meeting schedule goal Meeting budget goal	End of the project
Impact on the team	Team morale Skill development Team member growth Team member retention	End of the project
Impact on the customer	Meeting functional performance Meeting technical specifications Fulfilling customer's needs Solving customer's problem The customer is using the products Customer satisfaction	Months following project
Business success	Commercial success Creating a large market share	Years following project
Preparing for the future	Creating a new market Creating a new product line Developing a new technology	Years following project

But literature has also examined the broader impact of projects on the business. Pinto and Slevin [20] had acknowledged three aspects of project success concerning the implementation process, the perceived value of the project, and customer satisfaction with the delivered project outcome. Shenhar & Dvir [21] proposed a new way to look at project success. Rather than seeing projects as tasks that lead to the meeting time, budget, and performance goals, one should view projects in their broader sense. They suggested a model based on five project success dimensions, judged over different timescales (see Table 2). This model was selected to assess individual project success dimensions in this research.

3. The research model: The relationship between project management approach and project success dimensions

Organizations are using a particular project management approach to collect practices, expecting greatly improved project performance and project success. As a collection of practices, the project management approach collectively impacts different project success dimensions. However, one approach may have a more significant impact than others, and their impact could differ concerning different project success dimensions. As argued by some authors, the traditional project management approach, which exclusively pursues the success criteria of costs, time, quality, and meeting technical requirements, has become considered ineffective [25]. Previous studies analyzed the impact of individual approaches or specific project management practices, or management variables on project success, without considering the impact on different project success dimensions, as perceived in this research. Recognizing this as exploratory research, the authors intended merely to explore the research questions. The research framework (see Fig. 1) was developed to provide empirical evidence and test whether the agile and traditional approach differentiates concerning their impact on different project success dimensions, taking into account various management aspects. For research purposes, this research considered five questions and 25 hypotheses (see Table 3).

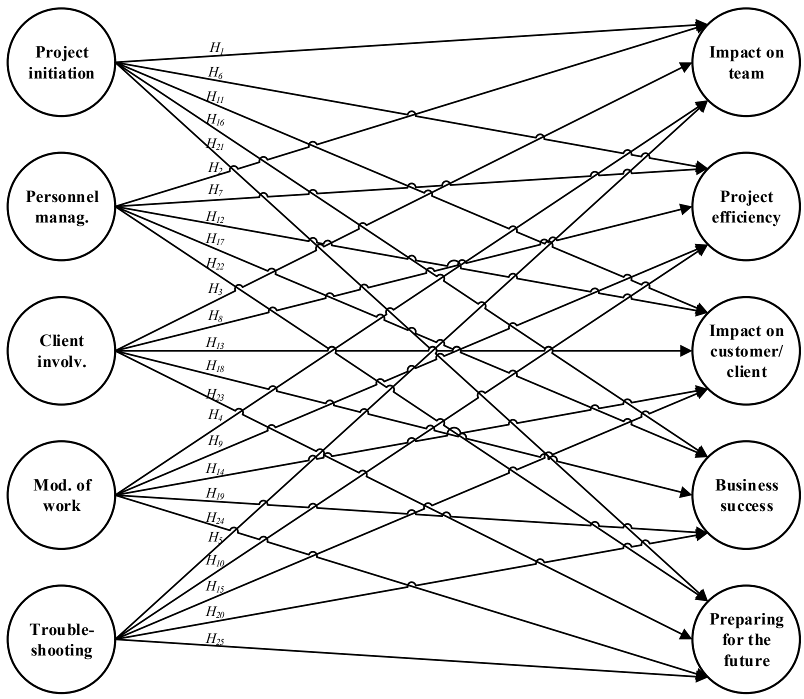

Fig. 1 The research model

Table 3 Research questions and hypothesis

Question 1	**How agile and traditional project management approach differentiate concerning their impact on project success dimension - Impact on the team?**
H_1	**Agile vs. Traditional approach in Project initiation and planning** - The project management approach is related to project success dimension - **Impact on the team**
H_2	**Agile vs. Traditional approach in Personnel management** - Project management approach is related to project success dimension - **Impact on the team**
H_3	**Agile vs. Traditional approach in Client involvement** - Project management approach is related to project success dimension - **Impact on the team**
H_4	**Agile vs. Traditional approach in Modularity of work** - Project management approach is related to project success dimension - **Impact on the team**
H_5	**Agile vs. Traditional approach in Troubleshooting** - Project management approach is related to project success dimension - **Impact on the team**
Question 2	**How agile and traditional project management approach differentiate concerning their impact on project success dimension - Project efficiency?**
H_6	**Agile vs. Traditional approach in Project initiation and planning** - Project management approach is related to project success dimension - **Project efficiency**
H_7	**Agile vs. Traditional approach in Personnel management** - Project management approach is related to project success dimension - **Project efficiency**
H_8	**Agile vs. Traditional approach in Client involvement** - Project management approach is related to project success dimension - **Project efficiency**
H_9	**Agile vs. Traditional approach in Modularity of work** - Project management approach is related to project success dimension - **Project efficiency**
H_{10}	**Agile vs. Traditional approach in Troubleshooting** - Project management approach is related to project success dimension - **Project efficiency**
Question 3	**How agile and traditional project management approach differentiate concerning their impact on project success dimension - Impact on the customer/client?**
H_{11}	**Agile vs. Traditional approach in Project initiation and planning** - Project management approach is related to project success dimension - **Impact on the customer/client**
H_{12}	**Agile vs. Traditional approach in Personnel management** - Project management approach is related to project success dimension - **Impact on the customer/client**
H_{13}	**Agile vs. Traditional approach in Client involvement** - Project management approach is related to project success dimension - **Impact on the customer/client**
H_{14}	**Agile vs. Traditional approach in Modularity of work** - Project management approach is related to project success dimension - **Impact on the customer/client**
H_{15}	**Agile vs. Traditional approach in Troubleshooting** - Project management approach is related to project success dimension - **Impact on the customer/client**
Question 4	**How agile and traditional project management approach differentiate concerning their impact on project success dimension - Business success?**
H_{16}	**Agile vs. Traditional approach in Project initiation and planning** - Project management approach is related to project success dimension - **Business Success**
H_{17}	**Agile vs. Traditional approach in Personnel management** - Project management approach is related to project success dimension - **Business Success**
H_{18}	**Agile vs. Traditional approach in Client involvement** - Project management approach is related to project success dimension - **Business Success**
H_{19}	**Agile vs. Traditional approach in Modularity of work** - Project management approach is related to project success dimension - **Business Success**
H_{20}	**Agile vs. Traditional approach in Troubleshooting** - Project management approach is related to project success dimension - **Business Success**
Question 5	**How agile and traditional project management approach differentiate concerning their impact on project success dimension - Preparing for the future?**
H_{21}	**Agile vs. Traditional approach in Project initiation and planning** - Project management approach is related to project success dimension - **Preparing for the future**
H_{22}	**Agile vs. Traditional approach in Personnel management** - Project management approach is related to project success dimension - **Preparing for the future**
H_{23}	**Agile vs. Traditional approach in Client involvement** - Project management approach is related to project success dimension - **Preparing for the future**
H_{24}	**Agile vs. Traditional approach in Modularity of work** - Project management approach is related to project success dimension - **Preparing for the future**
H_{25}	**Agile vs. Traditional approach in Troubleshooting** - Project management approach is related to project success dimension - **Preparing for the future**

4. The research method

This research was based on the PLS-SEM method due to its exploratory nature [11]. Aside from the theoretical interpretation in prior studies, to the best of authors' knowledge, dimensions of project management approach and project success still lacks in its empirical validation, concerning cross-sectional samples and diverse research populations, as well as from the lacks of inclusion of various organizational types, sectors, and industries in such studies. Shenhar *et al*. [22] have empirically validated only four factors of project success. Shenhar & Dvir [21] proposed the fifth factor's inclusion, "impact on the team", afterward. In time, the five-factor solution of project success was empirically tested with exploratory factor analysis (EFA) by Mir & Pinnington [26]. However, as a method of factor extraction, rather than to cofound factor solution on maximum likelihood (ML), the authors have used principal component analysis (PCA), which is a simple linear combination of variables; therefore, it cannot be considered as "true" factor analysis [27]. Similarly, the constitution of project management approach dimensions concerning their manifest variables has yet, to be empirically tested and validated within the context of various research environments and their specifics. Thus, rather than "confirm" factor structure, this research is focused more on exploring the relations between research dimensions. Nevertheless, to achieve this, construct reliability and validity for project success factors is carried out in section 5.1, while the factor structure of project management approach was mimicked by calculating the composite score across its 21 manifest variables (summation of respondents' scores). Specifically, following literature recommendations, four items were used to calculate respondents' score, for each of: "Project initiation" (Q30-Q33), "Client involvement" (Q39-Q42), and "Troubleshooting" (Q48-Q51), while five items were used in the same manner for: "Personnel management" (Q34-Q38) and "Modularity of work" (Q43-Q47).

4.1 Measures and questionnaire development

This research used the originally developed questionnaire for a self-reporting (subjective) assessment of project management approach and project success, as perceived by respondents. The questionnaire had five sections, with 66 questions in total. As an independent variable, the project management approach was operationalized with 21 questions and analyzed through differentiation between agile and traditional project management approaches (see Table 1). The variables were classified into five groups: (1) project initiation and planning, (2) personnel management, (3) client involvement, (4) modularity of work, and (5) troubleshooting. While the fife-dimension framework for assessing project success, as a dependent variable, consisted of (1) project efficiency, (2) impact on team, (3) impact on customer/client, (4) business and direct organizational success, and (5) preparing for the future, taking the project success assessment questionnaire proposed by Shenhar & Dvir [21]. The operationalization of project success was measured with at least four manifest variables for project efficiency, impact on the customer/client, five questions for impact on the team, business and directional success, and preparing for the future. To capture respondents' self-reporting assessment of project management approach, to differentiate responses between agile and traditional, a continuum of seven-point, bipolar Likert type scale was used [28], where a far-left point (i.e., 1) is a measure of a more agile approach, opposed to a far-right measure of more, traditional approach (i.e., 7). Given that they are different by nature, in contrast to the aforementioned, a unipolar, five-point Likert type scale was used [28] to measure responses regarding the state of project success factors (1-strongly disagree, 5-strongly agree).

4.2 Data collection and sample demographic

The questionnaire was distributed through the Project Management Institute (PMI) worldwide network. PMI is the world's leading project management organization with over 500,000 global members, project professionals, and over 300 Local chapters internationally. Data collection was done electronically, using surveymonkey.com for the distribution process. Invitations to fill out the questionnaire were sent by email to PMI global members, through local chapters, and posted in PMI LinkedIn and other professional groups. This research was based on a random sample method of project managers. The distribution process was conducted following Dillman's approach [29]; thus, only one reply was accepted from the respondents. The exact number of targeted project management professionals and response rate could not be specified, considering that PMI chapters worldwide distributed the questionnaire through their professional network, but they could not share the information about their contact list. After the two months, 314 responses were obtained; however, only 227 were treated as a "completed survey." 87 responses were omitted from the final respondents' database due to the potential risk of non-engaged bias, measured by the very low standard deviations in responses (below 0.2) or the low percentage of non-completed questions (below 70 %). To ensure sample representativeness, 227 respondents were compared with the omitted ones. The results show that there are no differences between these two groups. The final sample consisted of 167 males (73.6 %) and 60 females (26.4 %), from 49 different countries worldwide (42.7 % from Europe, 22 % from North America, 16.3 % from Asia,14.5 % from South America, 3.1% from Australia and1.3 % from Africa). 148 respondents had 10 or more years of project management working experience, and more than 80 % of respondents have a professional PM certification. The organizations varied in size with 43 (18.9 %) organizations with 1-50 employees, 30 (13.2 %) with 51-200 employees, 21 (9.3 %) with 201-500 employees, 27 (11.9 %) 501-1000 employees, and 106 (46.7 %) with over 1000 employees. Respondents came from organisations from diverse industries: 25 % from IT, 11.5 % finance & financial services, 8.8 % construction, machinery, and homes, 8.4 % telecommunications, 7.5 % utilities, energy, and extraction, 7.5% government, 5.3 % education, 4.8 % manufacturing, 4 % healthcare & pharmaceuticals, 3.1 % business support & logistics, 3.1% insurance, 2.2 % airlines & aerospace (including defence), 1.8 % food & beverages, 1.8 % transportation & delivery, and other industries have less than 1 %.

5. Data analysis, results, and discussion

The research model was evaluated using a two-step approach [11]. The assessment of the measurement model was carried out first. Empirical evaluation of the research model was carried out afterward.

5.1 Measurement model

To test the reflective measurement model of "Project Success," confirmatory factor analysis (CFA) was used. Hence, construct reliability, composite reliability, convergent, and discriminant validity were conducted [11]. A construct reliability test (Cronbach's α) and composite reliability (CR) were carried out following respectful literature recommendations [11,30]. Accordingly, the values of 0.70 and above are acceptable. Further, outer loadings and average variance extracted (AVE) were used to check convergent validity. Consequently, external loadings should be at least 0.7 and statistically significant ($t \geq 1.96$) [11], which was not the case for one item of "Business success" (Q55.3) and "Preparing for the future" (Q56.3). These items were removed from the measurement model [11]. Moreover, AVE values should be at least 0.5 for every measurement model construct [11]. All constructs have met this criterion. To assess discriminant validity, a Fornell-Larcker criterion was used [11]. Accordingly, the measurement model's discriminant validity is met if the reflective constructs have the strongest relationships only with its indicators (e.g., compared with any other construct) [11]. This criterion was also met for all constructs of project success. Finally, collinearity analysis was carried out using VIF (variance inflation factor). Since all of the VIFs were below the value of 3.3, collinearity was not an issue [11]. These values are shown in Table 4.

Table 4 The measurement model statistics

No.	Construct	Items	Outer-Loadings	α	CR	AVE	VIF	1	2	3	4	5
1	Impact on theteam	5	0.808-0.869*	0.896	0.922	0.702	2.058-2.783	**0.838**[FL]				
2	Project efficiency	4	0.733-0.813*	0.774	0.854	0.594	1.347-1.787	0.586	**0.771**[FL]			
3	Impact on the custom-er/client	4	0.804-0.873*	0.873	0.911	0.719	1.943-2.607	0.537	0.671	**0.848**[FL]		
4	Business success	4 (-)	0.759-0.851*	0.830	0.885	0.658	1.828-2.207	0.541	0.574	0.585	**0.811**[FL]	
5	Preparing for the future	4 (-)	0.719-0.827*	0.748	0.843	0.573	1.360-1.572	0.455	0.372	0.337	0.464	**0.757**[FL]

*α – Cronbach's alpha, CR – composite reliability, AVE – Average variance extracted; VIF – Variance inflation factor * – statistically significant, t ≥ 1.96; – Construct with removed indicators, [FL] – Fornell-Larcker criterion*

5.2 Structural model results and discussion

A bootstrapping technique with 5000 subsamples was used for structural model testing of path coefficients. The coefficient of determination (R^2 values) was found to be acceptable [11]. Thus, it could be said that the predictive power of the research model is valuable. An empirically validated and tested research model is given in Fig. 2. These results are shown in Table 5. Concerning the bipolar scale used to capture respondents' feedback on the project management approach, path coefficients (β) of statistically significant relationships ($t \geq 1.96$) with project success factors are also given in the same manner. This is shown in Fig. 3. Bearing in mind that the continuum of far-right point of the scale is oriented towards traditional (higher values) and far-left towards the agile approach (lower values), positive, higher values of path coefficients show strong alignment in traditional, and, opposite to aforementioned, negative values are aligned with agile. Results from Table 5 show that, in most cases, organizations from the research population initiate and plan their projects work traditionally. In contrast, within all other managerial aspects of the project management process, they gravitate more towards the agile approach.

According to the research results empirically tested and validated research model has confirmed 13 out of 25 hypotheses (see table 5, Fig. 2 and Fig. 3) which were defined to answer the research questions. Question 1: *How agile and traditional project management approach differentiate concerning their impact on project success dimension-Impact on the team?* 4 out of 5 hypotheses confirmed that the project management approach is related to project success dimension impact on the team. Namely, the more traditional approach to project initiation and planning, including higher level and complexity of upfront planning, clarity and stability of project scope and requirements, and linear or incremental development, has a higher positive impact on team satisfaction. It could be assumed that a more anticipatory approach is more desirable for the project team. On the other hand, a more agile approach in team collaboration and organization and a higher level of client involvement and commitment throughout the project life cycle have a higher positive impact on team satisfaction. This is not surprising as agile places a premium on people and their interactions (10). Question 2: *How agile and traditional project management approach differentiate concerning their impact on project success dimension-Project efficiency?* 1 out of 5 hypotheses confirmed that the project management approach is related to project success dimension project efficiency. Only in project initiation and planning results has shown a strong statistically significant difference between the agile and traditional approaches favoring traditional. A more traditional approach to project initiation and planning, including a higher level and complexity of upfront planning, clarity, and stability of project scope and requirements, has a more substantial positive impact on project efficiency over agile. According to this result, it could be assumed that heavy planning and clarity of scope and requirement are essential for meeting project schedule and budget goals. Question 3: *How agile and traditional project management approach differentiate concerning their impact on project success dimension-Impact on customer/client?* 5 out of 5 hypotheses confirmed that the project management approach is related to project success dimension impact on customer/client. While a more traditional approach to project initiation and planning has a higher positive impact on client satisfaction, all other managerial aspects favor an agile approach. Namely, client satisfaction has shown to be higher when a team collaborates and is organized in a more agile way, with frequent and close collaboration with the client. Also, even though the team is more satisfied with linear and incremental development, it has been shown here that clients value a more agile approach with higher modularity of work and frequent iterations with changes that could be easily implemented during the project. Question 4: *How agile and traditional project management approach differentiate concerning their impact on project success dimension-Business success?* 1 out of 5 hypotheses confirmed that the project management approach is related to project success dimension business success. Only for troubleshooting, referring to how changes in requirements are managed and implemented, results have shown a strong statistically significant difference between agile and traditional approaches, in favor of agile, when discussing the impact on project benefits in commercial value and market share. Question 5: *How agile and traditional project management approach differentiate concerning their impact on project success dimension-Preparing for the future?* 2 out of 5 hypotheses confirmed that the project management approach is related to project success dimension preparing for the future. Namely, a more traditional approach to project initiation and planning, including higher level and complexity of upfront planning, clarity and stability of projects scope, and a more agile approach in team collaboration and organization, has a higher positive impact on preparing for the future, meaning creating new technological and operational infrastructure and market opportunities.

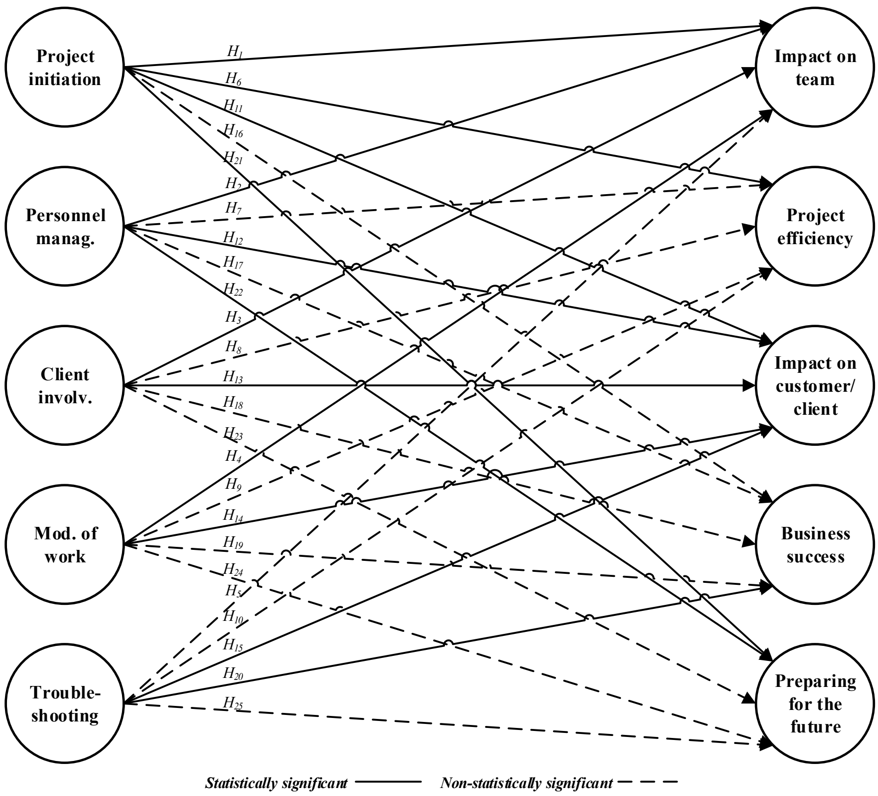

Fig. 2 Empirically validated and tested research model

Table 5 The structural model statistics

Exogenous variable →	Endogenous variable	R^2	β	*O.*	μ	δ	*t*	*p*	Hypothesis	Sig.
Project initiation			0.302	0.302	0.304	0.069	4.372	0.000*	H_1	*Yes*
Personnel management			-0.247	0.487	0.492	0.058	8.365	0.000*	H_2	*Yes*
Client involvement	Impact on team	0.261	-0.239	0.417	0.422	0.059	7.042	0.000*	H_3	*Yes*
Modularity of work			0.050	0.263	0.266	0.063	4.197	0.000*	H_4	*Yes*
Troubleshooting			-0.159	0.074	0.077	0.067	**1.101**	**0.271**	**H_5**	***No***
Project initiation			0.487	-0.247	-0.252	0.063	3.923	0.000*	H_6	*Yes*
Personnel management			-0.073	-0.073	-0.076	0.064	**1.145**	**0.252**	**H_7**	***No***
Client involvement	Project efficiency	0.346	-0.191	-0.105	-0.108	0.071	**1.483**	**0.138**	**H_8**	***No***
Modularity of work			0.002	-0.137	-0.138	0.072	**1.890**	**0.059**	**H_9**	***No***
Troubleshooting			-0.276	-0.034	-0.034	0.071	**0.478**	**0.633**	**H_{10}**	***No***
Project initiation			0.417	-0.239	-0.237	0.065	3.645	0.000*	H_{11}	*Yes*
Personnel management			-0.105	-0.191	-0.189	0.065	2.956	0.003*	H_{12}	*Yes*
Client involvement	Impact on customer/client	0.221	-0.135	-0.135	-0.135	0.067	2.019	0.044**	H_{13}	*Yes*
Modularity of work			-0.021	-0.159	-0.161	0.070	2.253	0.024**	H_{14}	*Yes*
Troubleshooting			-0.138	-0.266	-0.268	0.063	4.200	0.000*	H_{15}	*Yes*
Project initiation			0.263	0.050	0.050	0.079	**0.628**	**0.530**	**H_{16}**	***No***
Personnel management			-0.137	0.002	-0.000	0.073	**0.032**	**0.974**	**H_{17}**	***No***
Client involvement	Business success	0.312	-0.159	-0.021	-0.018	0.082	**0.251**	**0.802**	**H_{18}**	***No***
Modularity of work			0.014	0.014	0.016	0.092	**0.156**	**0.876**	**H_{19}**	***No***
Troubleshooting			-0.103	-0.245	-0.247	0.086	2.833	0.005*	H_{20}	*Yes*
Project initiation			0.074	-0.159	-0.156	0.081	1.971	0.049**	H_{21}	*Yes*
Personnel management			-0.034	-0.276	-0.274	0.072	3.819	0.000*	H_{22}	*Yes*
Client involvement	Preparing for the future	0.202	-0.266	-0.138	-0.140	0.085	**1.628**	**0.104**	**H_{23}**	***No***
Modularity of work			-0.245	-0.103	-0.102	0.095	**1.081**	**0.280**	**H_{24}**	***No***
Troubleshooting			-0.022	-0.022	-0.024	0.079	**0.284**	**0.776**	**H_{25}**	***No***

** statistically significant at **α** ≤ 0.005; ** statistically significant at **α** ≤ 0.05; β – path coefficient; O. – original sample; μ – sample mean; δ – standard deviation; t – t statistics (statistically significant at t ≥ 1.96)*

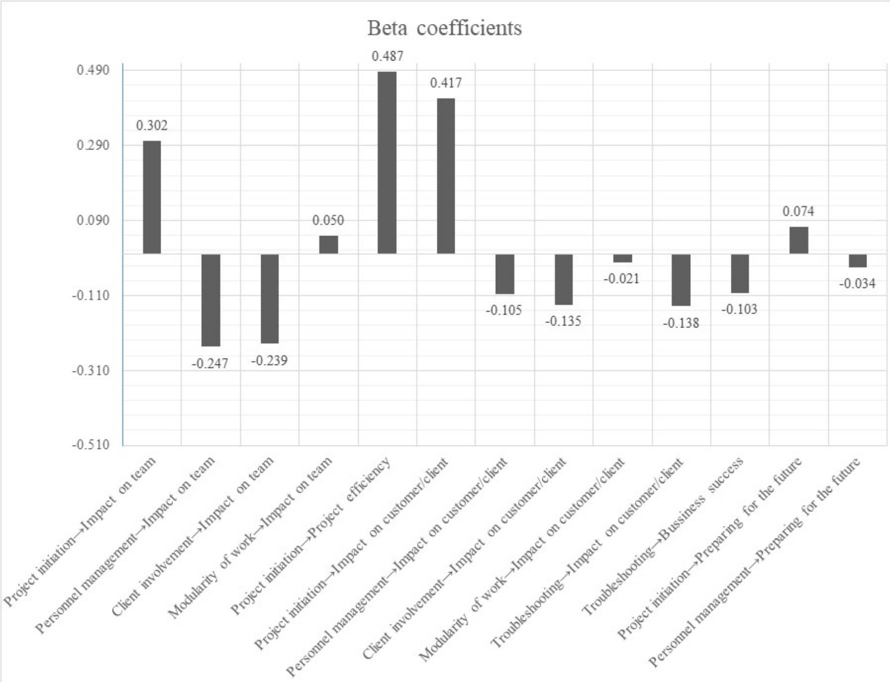

Fig. 3 Path coefficients of the empirically validated and tested research model

6. Conclusion

Taking a different perspective on the project management approach may provide additional insight into why and how a particular approach, in some managerial aspects, has a higher impact on different project success dimensions. Perceiving this as exploratory research, the authors intended merely to explore the latest research ground. This research considered five questions and 25 hypotheses for testing whether agile and traditional approaches differentiate concerning their impact on different project success dimensions and reveal these differences' nature. Research results denounced that, in most cases, the traditional approach is applied in project initiation and planning. It has proven to provide higher-level od project success, while, within all other managerial aspects considered in this research, they gravitate more towards the agile approach. Based on these results, we can conclude that when we talk about the project management approach, namely, agile and traditional, we should consider combining them, where each makes the most sense. By combining agile and traditional approaches, organizations can take advantage of some benefits of agile development without abandoning the stability provided by a traditional approach. Traditional project management is very comprehensive, and it has been proven to work in diverse project situations. At the same time, agile adds new ideas for addressing the unique project situations focusing on people and collaboration combined with the need to embrace change. This requires having the right agile culture and the proper alignment at the management and team level [30]. The most effective and most natural is to implement agile is under conditions commonly found in the software industry, but it is crucial to determine how much agility is enough. In today's changing environment, organizations are forced to improve risk management to be successful and achieve goals [31]. For each project decision, it is essential to consider the risks of too much versus too little agility and the counterpart risks of doing too much planning [32]. The project management approach should fit the requirements and circumstances of each project but also the project team. A multidisciplinary approach, intense communication, lateral connections between functional units are just some of the prerequisites for more efficient project management [33]. By combining different facets of knowledge about the development activities, project managers can tailor team members' workloads and modify team composition to improve collaboration, coordination, and information exchange [34]. The project management approach's choice, which determines how a project is planned and executed, is of strategic importance to any organization. The chosen project management approach is often cited among the top reasons projects fail [35]. Each organization must decide the best way to select the most suitable project management approach and whether to have one or more variations.

This work contributes to the existing literature by expanding the research related to project management contingency theory's evolving field. The research results gave more extensive evidence and findings that demonstrate that a more project-specific approach should be adopted by project managers, taking into account the desired impact on different project success dimensions.

This research is limited to the contrasting agile and traditional project management approach and project success using the model by Shenhar & Dvir [21]. Other dimensions of project success could be explored to deepen understanding. In the context of methodological approaches, the limitation is the use of bipolar, Likert-type scale. Thus, it was impossible to grasp a "true" negative relationship between endogenous and exogenous variables. Also, the use of the PMI network for distribution purposes might have, to a certain extent, some influence on responders' opinion, as well on the nature of obtained responses. The distribution process through the PMI network could have some influence on the responses obtained.

Future research should consider project characteristics as moderating variables. In-depth case studies should be conducted by comparing the traditional and agile approaches to see which project scenarios signal a better fit.

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Optimization of a multi-objective location model of manufacturing base considering cooperative manufacturing capabilities and service benefits

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A B S T R A C T

Improving customer satisfaction and shortening the manufacturing cycle have become common concerns of current manufacturers. This paper presents a multi-objective location model considering the maximization of collaborative manufacturing capabilities and service benefits. This method first uses the two dimensions of *customer share* and *market consumption* to segment customers, and identify the weight of various customer groups. Secondly, the space vector model (VSM) is used to calculate the matching between manufacturing capabilities and manufacturing requirements. Then build a multi-objective location model based on the two goals of collaborative manufacturing capabilities and service benefits. Finally, the model was tested with simulation data, which proved the validity and feasibility of the model. According to the simulation results, managers can accurately select the optimal manufacturing base from multiple candidate manufacturing bases with regard to less costs, shorter lead times, better manufacturing capabilities, better service benefits. In this paper, Fuzzy theory, Logit model and VSM are combined to salve the problem of manufacturing base location. Considering resources and service benefits of each manufacturing base, it is helpful to optimize the location of enterprises. From the academic and practical points, this study provides a new perspective for the location problem.

A R T I C L E   I N F O

Keywords:
Manufacturing base;
Location model;
Multi-objective model;
Optimization;
Decision-making;
Customer demand preference;
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1. Introduction

Enterprises need to get rid of the traditional production modes in order to meet the needs of the market and customers. Enterprises should form manufacturing alliance with other enterprises in the industry chain to achieve resource integration. The manufacturing enterprise is no longer an independent individual serving for the customer, but multiple manufacturing enterprises form a logical overall manufacturing alliance to jointly serve the demand side of the industrial chain. In the face of diversified and personalized customer demands, it is difficult for a single enterprise's resources and capabilities to adapt to rapidly changing market opportunities [1]. Manufacturing companies form a manufacturing alliance to decompose a complete manufacturing task into several sub-tasks. Each manufacturing company is only responsible for the manufacturing of one sub-task, which can shorten the manufacturing cycle [2]. Marković *et al*. pointed out collaborative manufacturing can improve the market competitiveness of enterprises [3].

At the same time, if enterprises want to maximize sustainable development, they need to identify customer groups. For every customer that an enterprise obtains, it has to pay a certain amount of investment in the past, but the returns brought by customers are not the same. In this regard, enterprises must seek out the customer groups that can bring value-added and lock in high-value customer groups. Fazlollahtabar pointed out that a major challenge in marketing work is to determine the best market, especially in market segmentation. Producers need to find high-value markets in order to bring more profits to enterprises [4]. Market segmentation is widely used in various industries, it can effectively help managers lock in high-value customers. Hajibaba *et al.* studied the impact of tourism on hotel management and subdivided the market [5].

Based on this, this paper proposes a location model of manufacturing bases in collaborative manufacturing environment, and studies from two aspects of maximizing the matching degree of collaborative manufacturing capabilities and maximizing service benefit. Firstly, the utility theory of Logit model is used to classify the customers (demand points) in the demand area. The customers are divided into Loyal customers, Problem customers, Gold customers and Taurus customers. According to the production situation, these four types of customers are given different weights. Secondly, the vector space model is used to measure the matching degree between the manufacturing capabilities of collaborative manufacturing partners and the manufacturing demands of customer. Finally, a multi-objective optimization model is established under the constraints of time, cost, collaborative ability and service benefit.

2. Literature review

2.1 Customer segmentation and location decision

Target marketing strategy is an important subject that has attracted much attention from the industry and academia. Market segmentation is a widely used method to study customer purchasing behavior [6]. Tan *et al.* studied the customer's personalized demands and the product structure. He believes that customer behavior affects the manufacturer's planning of candidate product module variants and the production strategy of personalized modules [7]. Wu *et al.* put forward a framework model reflecting enterprise customized production, which combines with organization information processing theory, three-dimensional concurrent engineering theory and resource dependence theory [8]. Han took professional conference organizers as research objects [9]. Zheng *et al.* studied the power demand of different regions through market segmentation, which provides a certain reference for the construction of the power industry [10]. According to the USFK base relocation project, Lee conducted the preference analysis on residential demand, location and site elements of the US air force to determine the location of the residential base [11]. Ghorui *et al.* combine with the market demand of consumers, who uses fuzzy analytic hierarchy process (FAHP) and ideal solution similarity ranking fuzzy technology (FTOPSIS) to select the location of shopping center construction [12]. In the parking lot location problem, Jelokhani-Niaraki and Malczewskil consider the interests of stakeholders and other groups, integrates GIS and multi-criteria decision analysis (MCDA) functions into the web platform, and provids an effective multi-criteria spatial decision support system (MC-SDSS) [13].

2.2 Cooperative manufacturing and location decision

In the industrial revolution, the production and operation system constantly pursues higher efficiency, which causes the manufacturing mode to show two unique characteristics: integrated manufacturing and intelligent manufacturing [14]. Samani *et al.* proposed a concept based on collaborative decision-making, using Analytic Hierarchy Process (AHP) and geographic social networks to select the location of public parking lots in Tehran [15]. Wang *et al.* studies the collaborative construction of wind farms and power to gas plants and establishes a collaborative location planning mathematical model based on the scenario analysis with the optimization objective of maximizing net investment income [16]. Au *et al.* used the feed forward neural network with error back propagation (EBP) learning algorithm and fuzzy analytic hierarchy process (FAHP) to establish the clothing factory location model [17]. Garcia *et al.* studied enterprise location considering regional accessibility, distance, cost, regional security, regional demand and other factors [18]. Cai *et al*. studied the decision-making problem of chemical selection. Considering the regional background air quality information, the emission of new manufacturing sites and the statistical model of local meteorological conditions, he used Monte Carlo optimization method to optimize the location of new chemical factory [19]. Habibi *et al*. proposed a multi-objective robust optimization model, which considered the impact of users, transfer stations, landfills, recycling plants and waste transport vehicles on the location of domestic waste recycling and disposal facilities [20].

3. Problem description

Aiming at the location model under the collaborative manufacturing environment, this paper studies from the two aspects of manufacturing capabilities and service benefit, involving the two-stage location problem and types of nodes: parts suppliers, manufacturing partners, manufacturing enterprises and customers (demand points). Assuming that there are d demand points in the area. To better meet customer demands, the enterprise plans to build several factories in this area. After field surveys, it is found that there are a total of m candidate manufacturing bases for the enterprise to choose. At the same time, it is found that there are s parts manufacturing enterprises can be used as collaborative manufacturing partners and l suppliers. The structural analysis model is shown in Fig. 1. Due to the different mechanism of suppliers and collaborative manufacturing partners, this paper only studies the enterprise location model in collaborative manufacturing environment.

Some parameters involved in this paper are defined in order to facilitate the follow-up study.

$S = \{S_1, S_2, \dots, S_s\}$: A set of collaborative manufacturing enterprises. S_i represents the i-th collaborative manufacturing enterprise, $i = 1,2,\dots,s$.

$M = \{M_1, M_2, \dots, M_m\}$: A set of candidate manufacturing bases. M_j represents the j-th manufacturing base, $j = 1,2,\dots,m$.

$D = \{D_1, D_2, \dots, D_d\}$: A set of demand points. $D_l$represents the l-th demand point, $l = 1,2,\dots,d$.

$R = \{R_1, R_2, R_3, R_4\}$: A set of demand point (customer) types. In this paper, customer groups are divided into four types.

$w = \{w_1, w_2, w_3, w_4\}$: A weight set of demand points. The weight set of demand points can be obtained according to the production and operation experience of the enterprise.

p_{ij} represents the distance between the collaborative manufacturing enterprise S_i and the manufacturing base M_j.

p^*_{jl} represents the distance between the manufacturing base M_j and the demand point D_l.

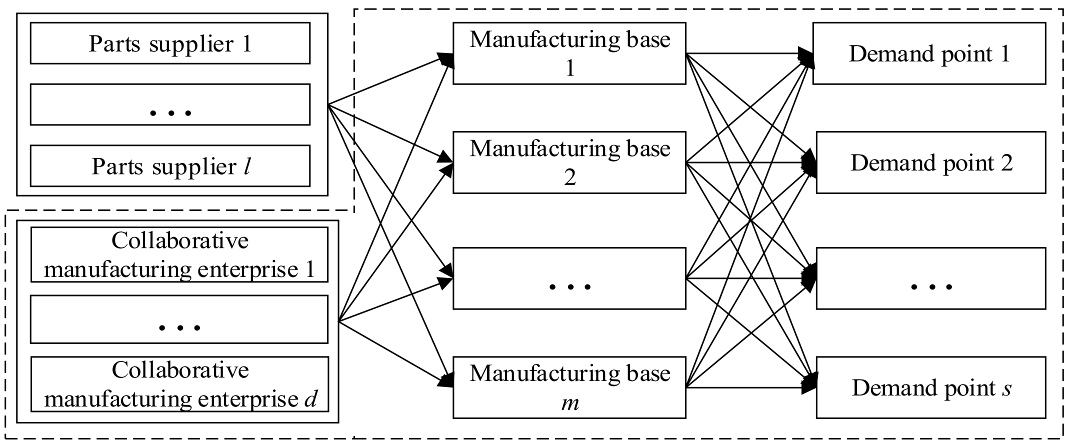

Fig. 1 The structural analysis model of manufacturing base

4. Proposed methodology

4.1 Customer segmentation based on customer value

In this paper, customer value can be interpreted as the present value of the total profits that customers may create for the enterprise in the future, assuming that the customer's current purchasing mode remains unchanged. It can also be understood that after enterprise adjusts operation strategies, the customer's consumption behavior for the product is enhanced, which in turn promotes the increase of corporate profits, and the customer may increase the profit value or revenue value of the enterprise in the future [21]. This paper classifies customer groups according to the two dimensions of *customer share* and *market consumption*, which is called customer classification matrix, as shown in Fig. 2.

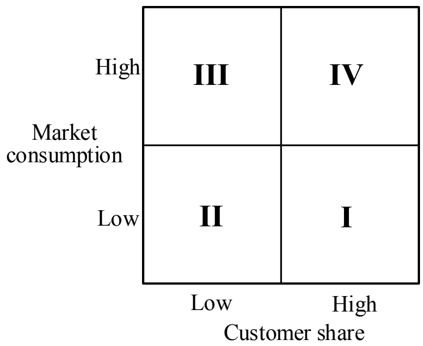

Fig. 2 Customer classification matrix

Market consumption proposed in this paper refers to the total market value of a region for a certain product in a period of time. To a certain extent, market consumption reflects the size and trend of regional demand for production. The demand of manufacturing products is mainly affected by regional economic factors (x_1), regional political and legal factors (x_2), regional information technology factors (x_3), regional cultural factors (x_4), regional customer group factors (x_5). Using the linear regression model, we get the linear regression prediction model of the total market consumption of product in the region, as follow

$$R = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + e \tag{1}$$

Here, a and e are structural parameters. The value of structural parameters has a direct impact on market consumption. In order to get more objective customer segmentation results, this paper uses the entropy method to study the structural parameters in Eq. 1. The specific steps are as follows.

Step 1: Selecting experienced professionals to form an expert group and using the 1-5 scoring method to evaluate the factors of the regional development status. Based on this, we can obtain the evaluation information and establish the evaluation matrix as follow.

$$EA = \begin{bmatrix} a_{11} & \cdots & a_{15} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{n5} \end{bmatrix}_{n\times 5} \tag{2}$$

Here, a_{ik} is the score of the k-th index by expert *i*, $k = 1,\ldots,5$.

Step 2: Calculating the proportion of the k-th index given by expert *i*.

$$\hat{a}_{ik} = \frac{a_{ik}}{\sum_{i=1}^{n} a_{ik}} \;, k = 1,\ldots,5 \tag{3}$$

Step 3: Calculating the entropy value of the k-th index

$$e_k = -\rho \sum_{i=1}^{n} \hat{a}_{ik}\, ln(\hat{a}_{ik}) \tag{4}$$

Here, $\rho = \frac{1}{ln\, n}$, n is the total number of experts, $e_k \geq 0$.

Step 4: Calculating the coefficient of variance of the k-th index

$$de_k = 1 - e_k \tag{5}$$

Step 5: Calculating the weight of each index.

$$\ddot{a}_k = \frac{de_k}{\sum_{k=1}^{5} de_k} \tag{6}$$

According to the index weight, the total market consumption of regional products is further predicted by Eq. 7.

$$R = \sum_{k=1}^{5} \ddot{a}_k x_k \tag{7}$$

Here, x_k is the mean value of the evaluation information.

According to the random utility theory in Logit model [22, 23], the expected utility of an enterprise's products or services can be composed of two parts: decision part and random part, as shown in Eq. 8.

$$ET_l = v_l + e_l \tag{8}$$

ET_l is the expected utility of product j, v_l is decision utility. e_l is random utility. Assuming there are C_n similar products in the market, $l \in [1, C_n]$.

According to the research results of Guadagni and Little, customer choice inertia is also an important factor influencing customer choice [24]. Therefore, the expected utility model can be further expressed as

$$ET_{lg} = v_{lg} + e_{lg} + \xi Last_{lg} \tag{9}$$

Here, ET_{lg} is utility of product h, when customers choose to purchase product l last time. ξ is the customer's purchase inertia coefficient. If $l = g$, $Last_{lg} = 1$. If $l \neq g$, $Last_{lg} = 0$.

Decision utility v_l is determined by a series of related variables.The decision utility can be calculated by Eq. 10.

$$v_l = \sum_{k=1}^{N} \alpha_k x_{lk} \tag{10}$$

Here, x_{lk} is the known observation value, and α_k is the weight coefficient. Comprehensiving Eqs. 9 and 10, the probability of choosing product h can be expressed as Eq. 11.

$$p_{lg} = \frac{e^{\xi Lasg + e_{lg} + \sum_{k=1}^{N} \alpha_k x_{lk}}}{\sum_{g=1}^{Cn} e^{\xi Last_{lg} + e_{lg} + \sum_{k=1}^{N} \alpha_k x_{lk}}} \tag{11}$$

The Markov prediction method can effectively predict the state that may appear in a certain time according to the current state. Markov method predicts that the customer's selection probability of product l at the t-th time is as follow.

$$(B_{1t}, B_{2t}, \cdots, B_{C_n t}) = (A_1, A_2, \cdots, A_{C_n}) \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1C_n} \\ p_{21} & p_{22} & \cdots & p_{2C_n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{C_n 1} & p_{C_n 2} & \cdots & p_{C_n C_n} \end{pmatrix}^t \tag{12}$$

B_{lt}represents the customer's choice probability of product l for the t-th time, and A represents the current selection probability.

4.2 Manufacturing capabilities matching

In the actual manufacturing process, it is difficult for manufacturing enterprises to obtain real and accurate manufacturing information of collaborative manufacturing partners. Fuzzy theory is considered to be an effective tool to solve the problem of uncertainty and fuzziness [25]. In this paper, triangular fuzzy numbers are used to obtain manufacturing capabilities of manufacturing partners.

$\hat{k} = (k^s, k^m, k^l)$ is a triangular fuzzy number, $k^s \leq k^m \leq k^l$, which membership function $u_{\hat{k}}(x)$ is shown as follows:

$$u_{\hat{k}}(x) = \begin{cases} \frac{x}{k^m - k^s} - \frac{k^s}{k^m - k^s}, x \in [k^s, k^m] \\ \frac{x}{k^m - k^l} - \frac{k^l}{k^m - k^l}, x \in [k^m, k^l] \\ 0, \qquad \text{other} \end{cases} \tag{13}$$

In this paper, five level linguistic variables $U = \{VB, B, M, G, VG\}$ are given to describe manufacturing capabilities of manufacturing partners. The corresponding triangular fuzzy numbers are shown in Table 1.

Table 1 Linguistic variables and triangular fuzzy numbers

Language variables	Symbol	Triangular fuzzy number
Very bad	VB	(0,0.1,0.2)
Bad	B	(0.2,0.3,0.4)
Medium	M	(0.4,0.5,0.6)
Good	G	(0.6,0.7,0.8)
Very good	VG	(0.8,0.9,1)

Vector space model (VSM) [26] is used to evaluate the matching degree of manufacturing demands and manufacturing capabilities.

Definition 1: manufacturing capabilities demand vector represents the manufacturing capabilities required for product manufacturing. Let $d = (d_1, d_2, \dots, d_d)$ represents the demand vector. d_j is the j-th product manufacturing demand, $j = 1,2, \dots, d$. The manufacturing capabilities vector of the i-th collaborative manufacturing partner is $m_i = (m_{i1}, m_{i2}, \dots, m_{id})$. m_{ij} is the mastery of j-th manufacturing capabilities by the i-th manufacturing partner, $i = 1,2, \dots s$.

Definition 2: manufacturing capabilities matching degree refers to the matching degree between manufacturing demands and manufacturing capabilities. Product manufacturing demand vectors are definite value. manufacturing capability vectors are obtained by triangular fuzzy number.

If m_{ij} is $\dot{k} = (\dot{k}^s, \dot{k}^m, \dot{k}^l)$, the triangular fuzzy number can be transformed into a definite value by Eq. 14.

$$m_{ij} = \frac{\dot{k}^s + 4\dot{k}^m + \dot{k}^l}{6} \tag{14}$$

According to VSM, the matching degree between manufacturing demands and manufacturing capabilities can be obtained by Eqs. 15 and 16.

$$\mathrm{sim}(M, s_i) = \cos(d, m_i),\ i = 1,2, \dots s \tag{15}$$

$$\cos(d, m_i) = \frac{\sum_{j=1}^{d}(d_j \times m_{ij})}{\sqrt{\sum_{j=1}^{d} d_j^2} \times \sqrt{\sum_{j=1}^{d} m_{ij}^2}}, i = 1,2, \dots s \tag{16}$$

Here, the higher the value of $\mathrm{sim}(M, s_i)$, the higher the matching degree.

4.3 Manufacturing base choice model

This paper gives a multi-objective optimization decision-making model for the manufacturing base. The first goal is to maximize the matching value, that is, the reliability of collaborative manufacturing alliance formed between the candidate manufacturing base and the collaborative manufacturing enterprises. The second objective is to maximize the service benefits under the customer preference, that is, the satisfaction degree of each candidate manufacturing base to the customer demand of different regions.

According to the characteristics of purchasing, production, transportation and sales of manufacturing enterprises, collaborative manufacturing mainly involves four influencing factors: cost, time, demand and collaboration.

The total production and operation costs of candidate manufacturing base M_j are divided into construction costs (c^1), transportation costs (c^2) and manufacturing costs (c^3). Among them, transportation cost (c^2) includes parts transportation cost (c_{ij}^2) and finished product distribution cost (c_{jl}^2).

$$C_j = c_j^1 + c_j^2 + c_j^3 \tag{17}$$

$$c_j^2 = \sum_{i=1}^{s} c_{ij}^2 + \sum_{l=1}^{d} c_{jl}^2 \tag{18}$$

In order to facilitate the study, this paper stipulates that the unit transportation cost is the same, which is expressed as $\hat{c}$, then the Eq. 18 can be expressed as:

$$c = \hat{c}\left(\sum_{i=1}^{s} p_{ij} + \sum_{l=1}^{d} p_{jl}^*\right) \tag{19}$$

The times of the manufacturing base M_j is the sum of the collaborative manufacturing times (t^1) and the delivery times (t^2), which can be expressed by Eq. 20.

$$T_j = \sum_{i=1}^{s} t_{ij}^1 + \sum_{l=1}^{d} t_{jl}^2 \tag{20}$$

Full coverage and joint coverage are selected to study the collaborative manufacturing capabilities. It is required that the collaborative manufacturing capabilities must meet the minimum manufacturing capabilities (Z_j) of manufacturing bases.

$$\sum_{i=1}^{s} g(p_{ij}) \geq Z_j \tag{21}$$

Among them, $g(p_{ij})$ is the collaborative manufacturing capabilities based on distance factor under the situation of full coverage, which can be calculated by Eq. 22.

$$g(p_{ij}) = \begin{cases} \mathrm{sim}(M_j, s_i), p_{ij} \leq r \\ 0, p_{ij} > r \end{cases} \quad i = 1,2,\ldots,s, j = 1,2,\ldots,m \tag{22}$$

Here, r is the full coverage radius.

Gradual coverage and joint coverage are selected to study the effective service of demand points. The sum of services of manufacturing base is required to meet the minimum service demands (Z_l^*) of each demand point.

$$\sum_{j=1}^{m} g(p_{jl}^*) \geq Z_l^* \tag{23}$$

Among them, $g(p_{jl}^*)$ are the service capacity based on distance factor in the context of gradual coverage, which can be calculated by formula (30).

$$g(p_{jl}^*) = \begin{cases} Q_i; p_{jl}^* \leq r_1 \\ Q_i - p_{jl}^*; r_1 < p_{jl}^* \leq r_2 \\ 0; r_2 < p_{jl}^* \end{cases} \quad i = 1,2,\ldots,s, j = 1,2,\ldots,m \tag{24}$$

Here, Q_i is the service capacity of i regions. r_1 is the full coverage radius. r_2 is the maximum service radius that can be perceived.

According to the previous analysis, this paper constructs a multi-objective optimization location model for manufacturing bases.

$$\max\ Z = \sum_{j=1}^{m} \mathrm{sim}(M_j, s_i)\, x_j \tag{25}$$

$$\max\ U = \sum_{l=1}^{d} w_l \sum_{j=1}^{m} g(p_{jl}^*)\, x_j \tag{26}$$

$$s.t.\ \sum_{j=1}^{m} g(p_{jl}^*)\, x_j \geq Z_l^* \tag{27}$$

$$\sum_{i=1}^{s} g(p_{ij})\, x_j \geq Z_j \tag{28}$$

$$\sum_{j=1}^{m} x_j \left(c_j^* + \hat{c}\left(\sum_{i=1}^{s} p_{ij} + \sum_{l=1}^{d} p_{jl}^*\right)\right) \leq C \tag{29}$$

$$\sum_{j=1}^{m} x_j \left(\sum_{i=1}^{s} p_{ij} + \sum_{l=1}^{d} p_{jl}^*\right) \leq T \tag{30}$$

$$Z_l^* \geq 0;\ \ Z_j \geq 0;\ \ c_j^* \geq 0;\ \ p_{jl}^* \geq 0;\ \ p_{ij} \geq 0 \tag{31}$$

$$x_j = \begin{cases} 0; & M_j \text{ is selected} \\ 1; & M_j \text{ is not selected} \end{cases} \tag{32}$$

Eq. 25 represents the maximum matching value. Eq. 26 represents the maximum service benefit. Eq. 27 is the service benefit constraint. Eq. 28 is the collaborative manufacturing capabilities constraint. Eq. 29 is the cost constraint. Eq. 30 is time constraint. Eqs. 31 and 32 express the value range of decision variables.

5. Results and discussion

5.1 Results

An equipment manufacturing enterprise A plans to build several factories in city B. According to the product sales records, 40 product demand points are obtained. Through the survey of the city, 18 candidate sites were obtained for site selection. At the same time, it was discovered that 20 manufacturing enterprises could act as collaborative manufacturing partners. According to the location model proposed in this paper, firstly, it is necessary to segment the customer groups for these 40 product demand points.

Four experienced professionals in the industry and six enterprise employees were selected to form an expert group. The 1-5 scoring method is adopted to evaluate the status quo of regional development and index weights, which evaluation information as shown in Table 2.

Table 2 Regional evaluation information (one demand point)

	Development status evaluation					Index weight evaluation				
	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5
Experienced professionals	4	2	4	4	5	3	1	5	4	3
	3	2	5	3	5	4	3	5	1	1
	5	4	5	5	1	1	2	2	5	1
	3	5	2	3	2	1	1	5	3	1
Enterprise employees	2	1	5	2	5	2	4	3	3	1
	2	3	4	5	5	2	1	2	1	1
	2	1	4	5	1	5	1	4	3	5
	4	4	3	5	4	5	3	5	5	4
	4	2	3	2	5	3	2	4	2	1
	2	1	1	1	3	3	1	4	1	3

According to the evaluation information, the evaluation matrix EA is established. Furthermore, the proportion matrix $\hat{a}$ of each expert for each index is calculated.

$$EA = \begin{bmatrix} 3 & 1 & 5 & 4 & 3 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 3 & 1 & 4 & 1 & 3 \end{bmatrix}_{10\times 5}$$

$$\hat{a} = \begin{bmatrix} 0.103 & 0.053 & 0.128 & 0.143 & 0.143 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0.103 & 0.053 & 0.103 & 0.036 & 0.143 \end{bmatrix}$$

Using the entropy method, the weight of each index can be calculated, as shown below.

$$de = (0.051,0.062,0.020,0.063,0.095)$$

$$\ddot{a} = (0.176,0.212,0.069,0.217,0.326)$$

According to Eq. 7, the total market consumption of regional products is predicted as follows.

$$R = \sum_{k=1}^{5} \ddot{a}\,x = 3.257$$

According to field investigation, it is found that there are three kinds of similar products in this area. The evaluation information of customers for these four products is obtained in the form of questionnaire survey, as shown in Table 5. According to the random utility theory, the expected utility (ET) of each product is calculated.

Table 3 The expected utility (ET) of each product (one demand point)

Products		Determining utility (v)	Random utility (e)	Inertia coefficient (ξ)	Expected utility(ET) $l \neq g$	$l = g$
Product 1 (A enterprise)		4	2	0.332	6	6.332
Similar products	Product 2	4	3	0.402	7	7.402
	Product 3	3	5	0.152	8	8.152
	Product 4	2	5	0.114	7	7.114

Based on the Markov prediction method, the selection probability of the next purchase of the demand point is predicted by using the Eqs. 11 and 12.

$$B = (0.331,0.404,0.157,0.109)$$

We can know the market share of enterprise A is 0.331. We can use the same method to calculate market share of other demand points, as shown in Fig. 3.

According to Fig. 3, there are 9 Loyal customers, 9 Problem customers, 10 Gold customers and 12 Taurus customers in 40 demand points. In the next production and operation reform, the influence weights of four types of customers on enterprise production are 0.05, 0.15, 0.45 and 0.35 respectively, that is $w = (0.05,0.15,0.45,0.35)$.

According to production requirements, enterprise A outsources the five sub-manufacturing processes of equipment manufacturing products and provides the minimum product manufacturing capacities requirements, $d = (0.419,0.502,0.562,0.516,0.441)$. Based on the experiences, an expert group was invited to use fuzzy theory to evaluate the manufacturing capabilities. According to Table 1, the manufacturing capabilities evaluation information of the collaborative manufacturing partner is obtained, as shown in Table 4.

The mean value of the triangular fuzzy number is obtained by the mean value method, and then, the triangular fuzzy number is converted into a certain value. The collaborative manufacturing capabilities vector m_i of collaborative manufacturing partners is shown in Table 5.

The matching degree is calculated, as shown in Table 6.

In order to ensure the smooth delivery of products, the manufacturing capabilities matching degree ≥ 0.9 is selected to participate in the product manufacturing process. s_3, s_4, s_6, s_{11} are selected. The total collaborative manufacturing capabilities of enterprise A is 11.428. The collaborative manufacturing capacity of 18 candidate manufacturing bases is shown in Table 7.

The 40 product demand points, 20 collaborative manufacturing partners and 18 manufacturing enterprise candidate points are scaled down and drawn on the plane of [0,100]×[0,100]. The location relationship and information are shown in Fig. 4 and Table 8.

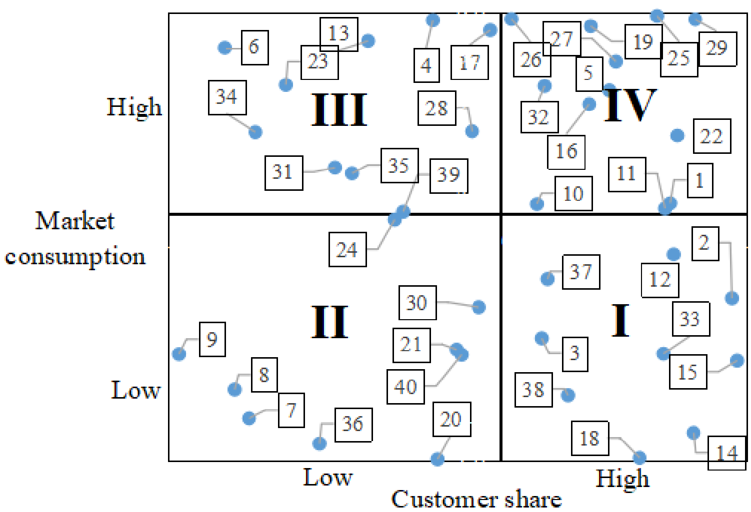

Fig. 3 Demand points subdivision graph

Table 4 Fuzzy value of manufacturing capacity (one expert)

	m_i				
	m_{i1}	m_{i2}	m_{i3}	m_{i4}	m_{i5}
s_1	(0.8,0.9,1)	(0.4,0.5,0.6)	(0.2,0.3,0.4)	(0,0.1,0.2)	(0.8,0.9,1)
s_2	(0.2,0.3,0.4)	(0.6,0.7,0.8)	(0.8,0.9,1)	(0.8,0.9,1)	(0.6,0.7,0.8)
s_3	(0,0.1,0.2)	(0.6,0.7,0.8)	(0.4,0.5,0.6)	(0.2,0.3,0.4)	(0.6,0.7,0.8)
s_4	(0.8,0.9,1)	(0.6,0.7,0.8)	(0.4,0.5,0.6)	(0.8,0.9,1)	(0.6,0.7,0.8)
s_5	(0.6,0.7,0.8)	(0.6,0.7,0.8)	(0,0.1,0.2)	(0.8,0.9,1)	(0.4,0.5,0.6)
s_6	(0.4,0.5,0.6)	(0.2,0.3,0.4)	(0.8,0.9,1)	(0.6,0.7,0.8)	(0,0.1,0.2)
s_7	(0,0.1,0.2)	(0.6,0.7,0.8)	(0.8,0.9,1)	(0.2,0.3,0.4)	(0.8,0.9,1)
s_8	(0.8,0.9,1)	(0.8,0.9,1)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0.8,0.9,1)
s_9	(0.6,0.7,0.8)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0.8,0.9,1)	(0,0.1,0.2)
s_{10}	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0.2,0.3,0.4)	(0.4,0.5,0.6)	(0.8,0.9,1)
s_{11}	(0.6,0.7,0.8)	(0.6,0.7,0.8)	(0.8,0.9,1)	(0.4,0.5,0.6)	(0.6,0.7,0.8)
s_{12}	(0,0.1,0.2)	(0.8,0.9,1)	(0.2,0.3,0.4)	(0.2,0.3,0.4)	(0.6,0.7,0.8)
s_{13}	(0.2,0.3,0.4)	(0.8,0.9,1)	(0.2,0.3,0.4)	(0.8,0.9,1)	(0.4,0.5,0.6)
s_{14}	(0.6,0.7,0.8)	(0.6,0.7,0.8)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0,0.1,0.2)
s_{15}	(0,0.1,0.2)	(0.8,0.9,1)	(0.2,0.3,0.4)	(0.8,0.9,1)	(0.6,0.7,0.8)
s_{16}	(0.2,0.3,0.4)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0.2,0.3,0.4)	(0.4,0.5,0.6)
s_{17}	(0.8,0.9,1)	(0.8,0.9,1)	(0,0.1,0.2)	(0.2,0.3,0.4)	(0.8,0.9,1)
s_{18}	(0.6,0.7,0.8)	(0,0.1,0.2)	(0.8,0.9,1)	(0.6,0.7,0.8)	(0.2,0.3,0.4)
s_{19}	(0.6,0.7,0.8)	(0.8,0.9,1)	(0.4,0.5,0.6)	(0.2,0.3,0.4)	(0.4,0.5,0.6)
s_{20}	(0.6,0.7,0.8)	(0.4,0.5,0.6)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0.8,0.9,1)

Table 5 Collaborative manufacturing capabilities

	m_i		m_i
s_1	$m_1 = (0.314,0.752,0.224,0.691,0.849)$	s_{11}	$m_{11} = (0.076,0.728,0.514,0.968,0.965)$
s_2	$m_2 = (0.533,0.629,0.788,0.482,0.765)$	s_{12}	$m_{12} = (0.478,0.019,0.273,0.622,0.035)$
s_3	$m_3 = (0.397,0.945,0.976,0.188,0.802)$	s_{13}	$m_{13} = (0.457,0.528,0.811,0.466,0.238)$
s_4	$m_4 = (0.481,0.108,0.835,0.513,0.438)$	s_{14}	$m_{14} = (0.317,0.578,0.536,0.364,0.624)$
s_5	$m_5 = (0.701,0.141,0.426,0.261,0.772)$	s_{15}	$m_{15} = (0.348,0.025,0.076,0.138,0.569)$
s_6	$m_6 = (0.103,0.194,0.621,0.408,0.131)$	s_{16}	$m_{16} = (0.324,0.204,0.690,0.640,0.654)$
s_7	$m_7 = (0.915,0.651,0.668,0.772,0.850)$	s_{17}	$m_{17} = (0.646,0.518,0.195,0.676,0.971)$
s_8	$m_8 = (0.753,0.337,0.490,0.323,0.947)$	s_{18}	$m_{18} = (0.193,0.828,0.850,0.769,0.407)$
s_9	$m_9 = (0.391,0.408,0.271,0.480,0.376)$	s_{19}	$m_{19} = (0.375,0.586,0.852,0.439,0.565)$
s_{10}	$m_{10} = (0.892,0.243,0.437,0.952,0.896)$	s_{20}	$m_{20} = (0.403,0.843,0.604,0.748,0.819)$

Table 6 Matching degree (one manufacturing base)

Collaborative enterprises	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
$sim(M,s_i)$	0.900	0.982	0.913	0.913	0.844	0.876	0.974	0.884	0.974	0.894
Collaborative enterprises	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}	s_{17}	s_{18}	s_{19}	s_{20}
$sim(M,s_i)$	0.899	0.767	0.962	0.970	0.695	0.939	0.886	0.952	0.976	0.974

Table 7 Collaborative manufacturing capabilities of manufacturing base

Manufacturing bases	Collaborative capability	Manufacturing bases	Collaborative capability	Manufacturing bases	Collaborative capability
M_1	11.428	M_7	10.295	M_{13}	9.942
M_2	12.606	M_8	8.455	M_{14}	11.708
M_3	8.537	M_9	10.354	M_{15}	12.803
M_4	11.217	M_{10}	10.537	M_{16}	9.188
M_5	9.526	M_{11}	12.801	M_{17}	7.848
M_6	13.804	M_{12}	10.206	M_{18}	8.758

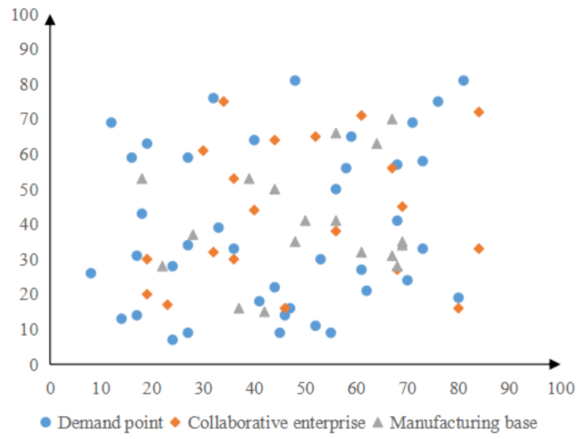

Fig. 4 Location diagram

Table 8 Manufacturing information (A part)

s	r	M	C	T	$g(p)$	$sim(M, s_i)$	Z	$[r_1, r_2]$	D	$g(p^*)$	Z^*	w
s_1	20.569	M_1	19.143	10.603	11.428	11.428	9.513	[30.351,32.393]	D_1	60.566	50.642	0.35
s_2	25.448	M_2	18.127	6.593	12.606	12.606	9.957	[28.689,29.833]	D_2	44.108	58.482	0.05
s_3	28.397	M_3	18.895	5.451	8.537	8.537	6.800	[33.552,35.048]	D_3	60.936	49.063	0.05
s_4	20.312	M_4	20.863	5.217	11.217	11.217	8.481	[28.768,30.501]	D_4	59.558	64.009	0.45
s_5	21.954	M_5	15.484	8.066	9.526	9.526	8.567	[31.658,33.155]	D_5	54.574	31.149	0.35

Based on the above calculation data, the location model is established according to the Eqs. 31 to 39. Assuming that the total cost is no more than 2 million and the delivery time is no more than 25 months, the location model is as follows.

$$\max\ Z = 11.428x_1 + 12.606x_2 + \cdots 7.848x_{17} + 8.758x_{18}$$

$$\max\ \ U = 0.35(60.566x_1 + \cdots 56.564x_{18}) + \cdots 0.15(60.566x_1 + \cdots 56.564x_{18})$$

$$S.t.\ \begin{cases} \begin{cases} 60.566x_1 + 44.108x_2 + \cdots 56.564x_{18} \geq 50.642 \\ \cdots \\ 60.566x_1 + 44.108x_2 + \cdots 56.564x_{18} \geq 66.354 \end{cases} \\ \begin{cases} 11.428x_1 + 12.606x_2 + \cdots 8.758x_{18} \geq 9.513 \\ \cdots \\ 11.428x_1 + 12.606x_2 + \cdots 8.758x_{18} \geq 15.624 \end{cases} \\ 19.143x_1 + 19.552x_2 + \cdots 15.621x_{18} \leq 200 \\ 10.603x_1 + 6.593x_2 + \cdots 9.447x_{18} \leq 25 \\ x_j = \begin{cases} 0; & M_j \text{ is not selected}, j = 1,2,\ldots,18 \\ 1; & M_j \text{ is selected} \end{cases} \end{cases}$$

The location model belongs to 0-1 integer programming model, which is solved by lingo software. According to the solution results, we can choose 4 candidate manufacturing bases (3, 4, 6, 11) to build. These 4 bases can cover all the demand points under the constraints of cost, time, collaborative requirements and service requirements.

5.2 Discussion

Changing time parameter constraints of the model, other parameters remain unchanged, the multi-objective value change trend of the model is shown in Fig. 5. As can be seen from Fig. 5, with the increase of manufacturing time constraint, the collaborative manufacturing capabilities and service benefits are increased. When the time constraint increases to a certain value, the multi-objective value remains constant, which no longer increases with the increase of time. The location problem involves many factors, only relaxing time constraints, which can increase target values within a certain range. But after a certain value, the time factor will no longer affect the target values.

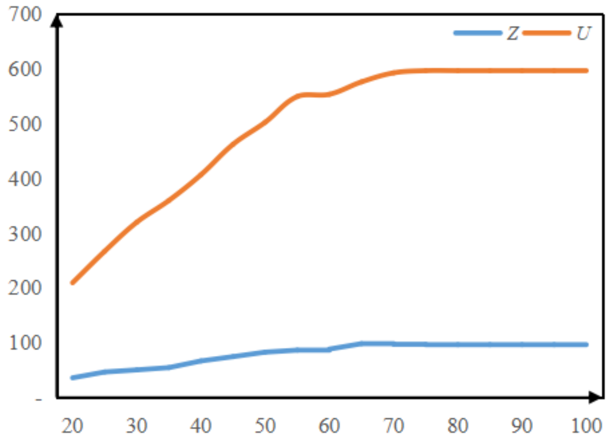

Fig. 5 Time parameter analysis

6. Conclusion

Collaborative manufacturing breaks the traditional manufacturing mode and realizes flexible production. Aiming at the location model of manufacturing base in collaborative manufacturing environment, this paper presents a multi-objective location model considering collaborative manufacturing capabilities and service benefit. Firstly, the Logit model is used to segment the customers and identify the influence weight of various customer groups. Secondly, the space vector model is used to calculate the matching degree between the manufacturing capabilities and the manufacturing demands. Then, a multi-objective location model is established based on the two objectives of collaborative manufacturing capabilities and service benefit. Finally, the simulation data is used to test the model. In this paper, the method considers manufacturing capabilities and service benefits of manufacturing base from a new research perspective, which is closed to the actual manufacturing status and also provides a reference for the subsequence location model. In this paper, the location problem relaxed the constraints of distribution vehicles. In the actual location problem, logistics distribution is also an important problem in the location problem. Therefore, in the next research, scholars should pay attention to the impact of logistics distribution on the location problem.

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A new management approach based on Additive Manufacturing technologies and Industry 4.0 requirements

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ABSTRACT

Nowadays, it is necessary to formulate and implement a development strategy in manufacturing enterprises, in line with the assumptions of the Industry 4.0 concept. In this context, a gap in the research has been observed in effective management methods, in order to gain a competitive advantage through the implementation and use of Additive Manufacturing (AM) technologies. The main purpose of the study is to build a new approach to management, based on the implementation of new AM technologies and good practice. This paper uses the detailed literature studies and results from the empirical research of some 250 Polish manufacturing enterprises; this material contains a sample thereof, processed into a new approach. The major contributions of the work are as follows: (1) identification of current management areas in which manufacturing companies focus their activities, in the context of Industry 4.0, (2) the establishment of the correlation between gaining a competitive advantage and implementing AM technologies in the context of Industry 4.0, (3) Defining the so-called AM4.0CARD as a new management approach, based on AM technologies and the requirements of Industry 4.0. Managers of manufacturing enterprises, thanks to the use of the proposed approach, may take a strategic decision, regarding the implementation of AM technologies, due to the possibility of forecasting the impact of such an investment on the improvement of the company's competitive advantage.

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1. Introduction

The fourth industrial revolution, also referred to as Industry 4.0, is based primarily on the close co-operation between systems related to cybernetic and physical components. Industry 4.0 has resulted in the high integration with the Internet of people and digitally controlled machines, information technologies and networking [1]. Elements and materials produced, or used for production, are identifiable at every stage and have been enhanced with the possibility of independently communicating with each other vertically, from individual components to the company's IT department and from the IT department to the components, in systems based on the assumptions of Industry 4.0. The flow of information is implemented horizontally between machines involved in the production process and the company's production system. The assets of the largest and fastest growing companies are innovative; we are talking about the latest and most innovative technologies and machines, apart from software and digital algorithms, permitted to operate on the network [2, 3]. The concept of Industry 4.0 significantly contributes to changes in manufacturing companies and particularly affects the need to constantly adapt to customer needs. Industry 4.0 introduces leading IT solutions into all aspects of production. Thanks to the use of advanced ICT technologies, it is possible to adapt production to customer expectations more accurately while maintaining low costs, high quality and efficiency and developing automation towards the implementation of cyber-physical systems and testing human-machine interactions [4, 5]. In connection with the digital revolution observed in industry, management theories are emerging, based on new technologies and achieving competitive advantages in the market, in tandem with the requirements of Industry 4.0.

The basis of Industry 4.0 is its advanced production technologies, which include additive, manufacturing (AM) technologies [6]. AM is treated as a combination of materials with the aim of obtaining a real object, based on 3D CAD data [6, 7]. Metals, ceramics, metal alloys, as well as plastics are used in these technologies. Additive manufacturing technologies, due to their specificity, increase flexibility in production and facilitate the speedy and hitch-free launch of a product. AM technologies are widely used in rapid prototyping and production, as well as in the manufacture of products with complex shapes, which would not otherwise be possible with traditional manufacturing methods. Thanks to the production capabilities achieved using AM technology, with special regard to the production of objects of any shape and structure, AM technologies are the perfect solution for an on-demand, customised production system and support more significant designs and manufacturing freedom to create innovation in Industry 4.0. Thus, machines using AM technologies are very versatile; changing the direction of production or of manufactured products does not require retooling of the production line, as is usually the case with traditional technologies. Thanks to this, time is saved and human participation reduced. Additionally, AM technologies usually recycle material [8].

Based on the analysis of the literature on the subject, we have determined that there are management theories applicable in the context of Industry 4.0. On the other hand, the development of AM technology is evident, as has been confirmed on the basis of empirical research on the use of AM technologies in western Poland, to name but one location. However, answers to the following questions are sought: (1) Does the implementation of AM technology increase a company's competitiveness on the market? (2) What factors influence the decision to implement AM technology? (3) What strategic goals can be achieved by implementing AM technologies?

This paper deals with problems related to management theory, as described in the research literature of 2018-2020, namely, the obtainment, in the market, of competitive advantages by manufacturing companies, due to use the modern technologies in the context of Industry 4.0. Our purpose, in this research, is to advance the literature on the relationship between competition within a manufacturing company and the implementation of AM, in the context of meeting a company's requirements *vis-à-vis* the Industry 4.0 concept. Therefore, a new management approach (CARD), based on AM technologies and the requirements of Industry 4.0 (so-called AM4.0CARD) is proposed.

2. Research methodology

The research was carried out in two stages: (1) analysis of the literature and (2) the empirical research to identify current areas of interest and management-oriented activities in the context of the implementation of AM technologies. In the first stage, current professional literature was analysed, highlighting the main management theories on achieving competitive advantage, verification methods, areas of application and limitations. We reviewed 35 articles published between 2018-2020. Articles obtained from databases (mostly Elsevier) were subjected to an analysis of the preliminary content, based on the titles of the articles and their abstracts. The publication period was set from 2018 to 2020. The knowledge contained in the articles was analysed and extracted, with particular attention being paid to management theory with aim of obtaining a competitive advantage, the correlation with Industry 4.0 and the models verifying the theory thereof and the possible applications and limitations to be encountered when applying a given theory. In the final step, we collected the data, analysed it and proceeded to write this paper. In researching the literature, a research gap was identified in the context of management theory, based on AM technologies with particular reference to Industry 4.0.

In the second stage of the research, at the end of 2019, we tested 250 Polish manufacturing companies from western Poland (from the Lubuskie Voivodeship, Lower Silesia, Opole, Greater Poland and West Pomeranian Voivodeship) in the metal (125) and automotive (125) industries. The tests were carried out using the survey method. The survey questionnaire included multi-choice, closed questions. Among the automotive companies, were 92 small enterprises, 29 medium enterprises and 4 large enterprises, while representatives of the metal industry comprised 95 small enterprises, 27 medium enterprises and 3 large enterprises. The respondents in the automotive industry were mostly representatives of the management (69) and company owners (32), specialist employees, including technologists, logisticians, designers, marketing employees (16) and company support employees, including assistants, accountants, administrative staff, etc. (8). In the metal industry, the respondents to the survey were mainly representatives of the management (72), owners and shareholders (36) and specialist employees, in the fields of quality, production, purchasing, design and construction, among others (13) and company support employees, including accountants and sales/sales department staff (4). The research group represents 1 % of manufacturing companies from the automotive industry and the metal industry, in western Poland [6] based on data from Central Statistical Office of Poland, Warsaw. In the second stage, through empirical research, the interest in AM technologies of respondents, who use AM in production was identified, which indicates the development of additive technologies.

In order to find the answer to our research question, correlation analysis was used. Correlation analysis is a statistical study that describes the strength of a linear relationship between two variables. The value characterising the relation is the correlation coefficient of the sample (r). It takes its values from the closed interval $<-1;\ 1>$. A value of -1 indicates there is a perfect negative correlation and a value of 1 indicates a perfect positive correlation. A value of 0 indicates no linear correlation [9].

Finally exploited is the capability of the Balanced Scorecard (BSC) to identify the relationship between competition within a manufacturing company and the implementation of AM technologies, in the context of meeting a company's requirements by combining the results of the literature review, the empirical research results and the correlation analysis results. The use of BSC can provide a manufacturing company’s strategy [10]. Therefore, a new approach to management (CARD), based on the implementation of AM technologies, was built using the Balanced Scorecard and it is for this reason that identification of the main management problems, needs to be concentrated on four strategic areas in production companies, namely, the customers (the sales market), the finances (including production resources), the processes (production processes) and development (research and development projects). The Balanced Scorecard is a tool that enables the identification of problems in given areas, together with the planning of strategic goals, activities and controls through evaluation of the measure. This tool allows the accurate perspective of actions to be analysed at specified time intervals, so that solutions to identifying problems can be planned while measuring the achievement of goals.

3. Results and discussion

3.1 Literature review results

In the literature on manufacturing, the changes refer to Industry 4.0 [11]. Manufacturing companies focus on the implementation of new technologies in order to meet market requirements and also face the challenge of adjusting manufacturing processes, keeping in mind strategies towards sustainable development, the proposal of products manufactured with a low energy input, using reduced levels of resources and low emissions of waste and exhaust gases. By analysing the literature on the subject, it was possible to identify the main areas in which manufacturing enterprises focus their management activities, dictated by the digital revolution of industry. Data obtained on the basis of literature analysis was collected and summarised in Table 1.

Table 1 Management theories aimed at competitive advantage according to the requirements of Industry 4.0

No.	Management theory aimed at competitive advantage	Aspects of Industry 4.0	References
1.	Theory based on technology-oriented alliances (the hiring of R&D scientists from competitors within the industry)	Technology implementation and development	[12]
2.	Theory based on sustainability in the context of a company's mainstream competitive strategy	Sustainability	[13]
3.	Theory based on sustainable development and inter-temporal trade-offs	Sustainability	[14]
4.	The competence-based view of submarket industrial evolution, that is, the convergence toward homogeneous or heterogeneous industry structures, e.g. the positioning of incumbents	Big data	[15]
5.	Theory based on the concept of relational rivalry (Competition between firms)	No direct correlation	[16]
6.	Theory based on the creative integration of several information and communication technologies (ICTs)	Networking, ICTs, Internet of things	[17, 18]
7.	Theory based on corporate social responsibility (CSR)	No direct correlation	[19]
8.	Theory based on effective risk management in technological innovation and the implications thereof	Big data	[20]
9.	Institutional theory and international entrepreneurship (internationalisation)	No direct correlation	[21, 22]
10.	Theory based on the product-service-systems (PSS) strategy	Networking, Internet of things	[23, 24]
11.	Theory based on the use of business models by management	No direct correlation	[25]
12.	Theory based on the accumulation of knowledge strategies and knowledge management	Big data	[26, 27]
13.	Strategy based on effective research and development (R&D)	Technology development and implementation, big data	[28]
14.	Theory based on management of the green supply chain (GSCM)	Sustainability	[29]
15.	Method based on the synergy effect	Networking	[30]
16.	Theory based on the development of a product and the portfolio design method	Networking, big data, technology development and implementation	[31, 32]
17.	Theory based on identifying and implementing the best technology	Additive manufacturing, technology development and implementation	[33]
18.	Theory based on the management of a sustainable supply chain (SSCM)	Sustainability	[34]
19.	Theory based on business analytics in manufacturing:	Big data	[35]
20.	Smart manufacturing (SM)	Smart manufacturing, Internet of things, big data, building blocks, additive manufacturing	[36]
21.	Theory based on improving the systematic learning within a factory based on the level of maturity	Big data, smart manufacturing, technology development and implementation	[37]
22.	Theory based on implementing project management good practices and lean production methodologies	Additive manufacturing, smart manufacturing, big data	[38]
23.	Methodology for the design of agile product development networks	Networking, Internet of things	[39]
24.	Theory based on open innovation (OI)	Technology development and implementation, networking	[40]

An analysis of the management theories, presented in Table 1, indicates that 20 are correlated with Industry 4.0 while the remaining 4 have no direct correlation thereto. In carrying out further analysis of the data in Table 1, the data was divided into those main areas on which management theories focus and into which the theories were divided, according to the examples of Industry 4.0 to which they applied. To this end, theories were analysed and divided into five main groups or areas on which management activities focus: (1) company—environment relations; (2) company relations—other company relations; (3) processes; (4) products; (5) knowledge and competences. The division of theories into main areas of activity is presented in Table 2.

Table 2 Division of management theory in the area

Management area	The sequence number of the theory (from Table 1)
Company relations—environment	2, 3, 7, 9, 14, 18
Company relations—other company	1, 5, 24
Processes	6, 8, 11, 15, 17, 19, 20, 22
Products	10, 16, 23
Knowledge and competences	1, 4, 6, 12, 13, 19, 21, 24

The literature analysed presents the current management theories that are applied in the context of Industry 4.0. When analysing the data collected in Table 1 and Table 2, there is a visible tendency for manufacturing enterprises to focus on management in two, main areas, namely: processes and knowledge and competences. In addition, there is a clear tendency that most theories are correlated with Industry 4.0 and are applicable in aspects such as: big data, networking, the Internet of things, smart manufacturing, etc. Changes related to Industry 4.0 shape the trend, and force companies to adapt to the expectations of a competitive market. The changing needs of customers mean that, ever more frequently, companies are forced to react quickly and thus to modernise production lines. This is a necessary process but it is time consuming and requires considerable resources. Thanks to the use of AM technology, the use of flexible production, reduces production time, reduces the need to change the production line, allows products to be produced in any shape and reduces human participation in the production process. AM technologies allow products to be produced, based on 3D CAD data, by adding material, layer-by-layer to create a solid object and thus solve various Fourth Revolution issues. However, we have not found an approach to management, based on the implementation of AM technologies in the context of planning strategic action, with the aim of achieving a company's competitive edge. By proposing a new approach, based on the implementation of AM technology, in the context of Industry 4.0, we intend to present the impact of obtaining a competitive advantage by a production company implementing AM technology, using the results of the literature research, the results of the empirical research and the strategic analysis tool.

3.2. Empirical research results

The results obtained were subjected to statistical analysis in the Statistica v.13.3 programme and we examined the correlation between the results obtained. In order to examine the validity of hypothesis 1, we analysed the correlation between the research results related to competitive advantage and the motives for implementing AM technology in the enterprise. The results were collected and are presented in Table 3.

Analysing the results of the statistical surveys obtained, we noticed that the highest correlation occurs between competitive advantage and freedom in product design. Probably, the companies participating in the survey see a real opportunity in gaining a competitive advantage by offering consumers the opportunity to buy any product, personalised according to the customer's expectations. In addition, the motive, indicated for the implementation of AM, suggests that companies want the possibility of quickly transforming production lines in order to be able to produce any product, depending on the needs of the market. The indication for this motive, for the implementation of AM, also suggests that companies want to be able to produce products of any shape, even those with the most complex geometry which could not be produced using traditional, manufacturing methods. In addition, companies see that a competitive advantage can be gained by not having assembly lines, but rather, by having products personalised, using materials efficiently and responding quickly to market needs.

We also examined the correlation between the results of the research, as related to knowledge about AM and competitive advantage. The research covered factors indicating competitive advantage and the factors describing knowledge prerequisite for the implementation of AM technologies, namely: research results related to interest in implementing AM technologies. This factor was chosen because employees' knowledge about AM technology should include knowledge about processes to which AM technologies (and the methods related to AM) can be applied. The data was collected and is presented in Table 4.

Table 3 Correlation between motives for implementation AM technologies and competitive advantage

Relations	Correlation	$r2$	t	p
Cost reduction/competitive advantage	0.261347	0.068303	4.255292	0.000030
Effective use of material/competitive advantage	0.399677	0.159742	6.852541	0.000000
Freedom in product design/competitive advantage	0.476172	0.226740	8.510392	0.000000
No assembly/competitive advantage	0.411996	0.169740	7.106148	0.000000
Product personalisation/competitive advantage	0.411996	0.169740	7.106148	0.000000
Quickly reaction for the needs of market/competitive advantage	0.371527	0.138032	6.289171	0.000000
Optimisation of product function/competitive advantage	0.329615	0.108646	5.486935	0.000000
Development/competitive advantage	0.034717	0.001205	0.545943	0.585598
Product quality/competitive advantage	0.095248	0.009072	1.503779	0.133916
Effectiveness/competitive advantage	-0.062487	0.003905	-0.983990	0.326083
Waste or energy reduction/competitive advantage	-0.035784	0.001280	-0.562747	0.574117
Employee reduction/competitive advantage	-0.050812	0.002582	-0.799608	0.424706

Table 4 Correlation between interest in implementing AM technology and competitive advantage

Relations	Correlation	$r2$	t	p
FDM/competitive advantage	0.063443	0.004025	1.001124	0.317743
LOM/competitive advantage	0.095360	0.009093	1.508599	0.132674
DLP/competitive advantage	0.193372	0.037393	3.103808	0.002132
PolyJet/competitive advantage	0.159730	0.025514	2.548154	0.011434
DMLS/competitive advantage	0.485181	0.235401	8.738014	0.000000
SLS/competitive advantage	0.063443	0.004025	1.001124	0.317743
SLA/competitive advantage	0.226348	0.051233	3.659508	0.000309
EBM/competitive advantage	0.226348	0.051233	3.659508	0.000309

The results of the statistical analysis indicated that the highest correlation exists between the interest in implementing the DMLS method and competitive advantage. The DMLS method allows the creation of complex shapes by the selective melting of metal powders that would not have been possible using traditional, manufacturing methods. Once again, companies see a competitive advantage in implementing the AM method that allows the design and manufacture of products of any shape, depending on customer expectations and market needs. In addition, a significant correlation was observed for the SLA (Stereolithography) and EBM (Electron Beam Melting) methods. Both methods are used in rapid prototyping. The SLA method involves hardening the resin by laser, allowing the rapid production of plastic prototypes. The EBM method uses an electron beam to melt metal powders, allowing precision parts to be made in a vacuum.

On the basis of the research results, both from analysis of the literature and the empirical research results from 250 Polish manufacturing enterprises, a new management approach was built, based on implementing AM technologies in manufacturing companies, namely the AM4.0 CARD.

3.3. AM4.0CARD – A new approach to management, based on the implementation of a new Additive Manufacturing technologies

The proposed approach is based on a specific, innovative group of AM, the benefits of the implementation of which appear in all production areas. In order to define the strategic action for a manufacturing company, in the context of an increase in competitive advantage, due to the implementation of AM and the adjustment to the requirements of the Industry 4.0 concept, the Balanced Scorecard tool was used. On the basis of data from Table 1, main management areas were identified, which were presented in Table 2. The most frequently discussed area in the literature analysed were processes. By examining process theories, it appears that they are related to Industry 4.0 in the following aspects: Additive manufacturing, big data and networking. The second area is knowledge and competences; it appears that these are related to Industry 4.0 in the aspect of technology development and implementation. The third area is a company's relationship with the environment and then the relationship of companies with one another. In the case of relationships, a link to Industry 4.0 has been identified in the aspects of sustainability, technology development and implementation. The last area are products, in which association with Industry 4.0 has been identified; this area is in the areas of Networking and the Internet of Things (IoT). Examination of management theories associated with Industry 4.0 has identified four main areas of management: process, product, knowledge and management and lastly, relationships. Based on the results of empirical research, the correlation between the motives for implementing AM technology declared by the manufacturing companies surveyed and a defined competitive advantage was examined. The results of the empirical research indicate a set of factors describing competitive advantages, including new material, adaptation of new manufacturing technologies, investments, personalised products, the management of suppliers and reductions in the waiting time for products. A significant correlation was observed in the case of freedom in product design: the absence of an assembly line, product personalisation, the effective use of material, quick reaction to the needs of the market, improvement in the function of the product and a reduction in costs. Additionally, a significant correlation was observed in the following factors, new material, adaptation of new manufacturing technologies, personalised products and the management of suppliers. Based on the results of an analysis of areas of management and factors correlated with competitive advantage, strategic goals were defined; this process is shown in Table 5.

The measures in Table 5 were defined on the basis of strategic goals. When designing strategic goals and measures, we took into account the results of the correlation analysis of the motives for implementing AM technology and the factors defining competitive advantage, as well as the results of the literature research. The measures have been designed to allow verification of progress and achievement of strategic goals. Above all, significant interest in laser technologies (e.g. DMLS) and the factors affecting decisions on implementing AM were taken into account: cost reduction, reduction in production times, reduction in barriers to design and in barriers to manufacturing a wide variety of shapes, etc. The perspectives of those actions taken, for implementing strategic goals, based on adopted measures, in accordance with Balanced Scorecard methodology, are formulated in Table 5.

The proposed approach based on the use of AM technology in combination with the theories contained in Table 1, is a new approach, because it directs the enterprise concerned to focus its management activities on specific, innovative manufacturing technology. The approach thus proposes to focus on the new AM technology, enabling the production of finished products and structures of virtually any shape, thereby reducing the assembly stage and human participation. The company's focus on manufacturing with AM technology can help it gain a competitive advantage by being able to respond quickly to market needs without having to switch production lines to a new product, allowing experimentation and prototyping before making large-scale production decisions, which contributes to effective knowledge management and competence in products and processes, as well as to the effective management of resources. The research results may prove useful for manufacturing companies from the metal and automotive industries which are focussed on development and achieving competitive advantage, primarily in the area of manufactured products, product portfolio and quick response to market needs. The main limitations may be differences in the level of development of Polish industry, in relation to other countries in the world. It should be emphasised that the proposed approach was created on the basis of an analysis and empirical research of the literature conducted in metal and automotive manufacturing companies in western Poland (Europe). The proposed approach is the first step to creating an individual, long-term strategy, based on the use of the new AM technology. Creating a long-term strategy should take into account the profile and individual capabilities of the company.

Table 5 AM4.0CARD – A management approach based on the implementation of AM technologies for manufacturing companies in the context of industry 4.0

Perspective	Problem	Strategic goal	Measure	Value	Actions
AM4.0 Customers	Inability to produce a product that meets customer expectations	Adopt and implement AM technology	The number of AM technologies selected, *via* analysis, resulting in the implementation of strategic goals	≥ 3	1. Analysis of new and potentially adaptable production technologies and the selection of a minimum of 3 AM technologies 2. Testing the technology in an external enterprise (research and development unit) before deciding on implementation 3. Comparative analysis of implementation assumptions and the results of empirical research 4. Analysis of the quality of products obtained, using current and envisaged technology
	Limitations in obtaining a product with complex geometry	Product personalisation and freedom in product design			
AM4.0 Finances	Costs of employing production workers	Reduction of employee participation in the production process	Adaptation of AM technology using a laser, e.g. DMLS – a method reducing the assembly stage, allowing the serial production of products of any geometry without the need to retool the machinery Learning and training in the use of new AM technologies	1	1. Selecting a technology that meets the objectives of achieving strategic goals 2. Analysis of the adaptability of new, manufacturing technology 3. Decision to implement the new AM technology 4. Implementation
	Costs associated with the need to change machinery	Quick response to changes and market needs and reduction of conversion costs			
	The relatively large amount of waste material that cannot be recycled	Effective use of material	Indicator of waste material	< 10 %	1. Measurement and analysis of the amount of waste material 2. Control in the management of materials 3. Analysis of emerging, innovative materials in terms of their adaptability to the production process
AM4.0 Processes	Long waiting times for the product	Reduction in production times by reducing the assembly stage	Time of production	-15 %	1. New technology in the production process 2. Adaptation of technology to the requirements of the process and of the product 3. Testing the possibility of obtaining any shape, using AM technology 4. CAD design 5. Production
	Technological limitations in the production of products	Producing products of any shape	The possibility to obtain any shape throughout the production process	100 %	
AM4.0 Development	No access to models	-	-	-	1. New, production process technology 2. Learning and training in the use of new AM technologies 3. Acquiring knowledge and competences through experience in the use of AM technologies
	No R&D activities	Increased level of knowledge and competence in the use of AM technologies	The possibility of acquiring new knowledge and competence	-	

Based on the research results obtained, it can be assumed that the introduction of AM technology into Polish manufacturing companies may contribute to increased interest in Polish products by other EU countries as also to contributing to an increase in the level of exports and competitive advantage. In this matter, a key role is played by the costs associated with production, which shape the price of a given product. The additive manufacturing technology facilitates the production of ready-made structures, the assembly of which would be impossible or at least very difficult using conventional manufacturing methods. In addition to a significant reduction in waste and the maximum use of materials, the production of structures, with complex geometry but without an assembly stage, is the most obvious of the competitive advantages.

4. Conclusion

The proposed approach, namely, the AM 4.0CARD, based on the adaptation of AM technology to manufacturing companies, can be introduced in companies that are focussed on development and continuous improvement. This approach is different from that analysed (Table 1) because it focusses on one specific, innovative group of additive manufacturing (AM) technologies. The AM technology-based approach allows the production company to adapt processes and organisations to the changes dictated by Industry 4.0. Thus, the company, using the proposed approach, can gain a competitive advantage, in a relatively short time, by reducing waste, reducing human participation in the process and producing products of any shape which require no further processing or assembly. AM technologies allow products with a complex geometry to be produced, which would not otherwise be possible, using traditional technologies. This is a huge opportunity for manufacturing companies, because it allows quick responses to the changing needs of the market, without having to re-invest in the machine park and retool. Thus, the time and the amount of the resources, involved in production, are saved. The proposed approach indicates the goals and how they are achieved, which is the scenario for the next step in the implementation of AM technology.

The main limitation to the approach, based on the adaptation of AM technology, is its limited potential for usability in resource-limited enterprises. Unfortunately, the costs of purchasing machines using AM technologies and the costs associated with adapting infrastructure and training personnel are still high. In this case, companies considering implementing AM technology should make an accurate estimate of the costs and the return on investment, taking into account the actual cost of the investment and all the benefits of using AM technology, the efficient use of materials, the reduction of waste, the reduction of the number of employees involved in the production process, freedom to design and produce products without having to change the machine park and to produce products with a complex geometry that could not be produced by traditional manufacturing methods – all of which can really contribute to increasing the company's financial result over a relatively short period, by introducing new products onto the market. In addition, it should be emphasised that the theory was built based on an analysis of the scientific literature and solely on the basis of research carried out in a representative group of 1 % of Polish manufacturing companies in two industries, in western Poland (Europe), the automotive and metal industries. The research was conducted at the end of 2019, which also suggests that it is worth conducting research in the next period, in order to examine changes and evaluations. Another limitation to the application of the proposed theory is the material used in production. Not every material can be used in AM technologies. Sometimes, the inability to change the material used for production can completely waste the chance and purpose of adapting to AM technology. Therefore, an in-depth analysis of the adaptation or replacement of AM technology in a production company is needed, based on the parameters of current production methods and the parameters of the AM technology selected. This is the research direction proposed by the authors of the article.

Further research should be aimed at analysing the possibilities of implementing AM technologies and directing further actions to designing a universal solution to decision making. It is worth emphasising that a new approach will be built in order to take decisions about the implementation of AM technology in a production company, taking into account all relevant, production parameters.

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- International Conference on Machine Learning and Deep Learning in Manufacturing, March 15-16, 2021, London, United Kingdom.
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- 6th International Conference on 3D Printing Technology and Innovations, May 24-25, 2021, Berlin, Germany.
- 38th Global Summit on Nanoscience and Technology, June 21-22, 2021, Osaka, Japan.
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