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Scope and topics

Advances in Production Engineering & Management (*APEM journal*) is an interdisciplinary refereed international academic journal published quarterly by the *Production Engineering Institute* at the *University of Maribor*. The main goal of the *APEM journal* is to present original, high quality, theoretical and application-oriented research developments in all areas of production engineering and production management to a broad audience of academics and practitioners. In order to bridge the gap between theory and practice, applications based on advanced theory and case studies are particularly welcome. For theoretical papers, their originality and research contributions are the main factors in the evaluation process. General approaches, formalisms, algorithms or techniques should be illustrated with significant applications that demonstrate their applicability to real-world problems. Although the *APEM journal* main goal is to publish original research papers, review articles and professional papers are occasionally published.

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Optimization of process parameters for machining of Al 7075 thin-walled structures

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A B S T R A C T

The aim of this paper was focused on research in order to improve the manufacturing of aluminium alloy thin-walled components through the optimization of milling process parameters. The methodology for optimization of milling parameters is developed and presented. The influence of the tool path strategy, wall thickness and feed rate on the machining time, dimensional accuracy deviation, shape and position accuracy deviation, and surface roughness in the case of line-type thin-walled parts machining were analysed. Based on the analysis of experimental results, the corresponding empirical models of responses were identified. Optimization of results was conducted using response surface methodology. Verification of optimization results was executed using two additional experiments. The results from experimental verification show a satisfactory matching with calculated optimal values. The basic scientific contribution of the paper relates to the development of a methodology for optimization of machining parameters for milling of thin-walled structures of aluminium alloy using an ANOVA method, Central Composite Design experiment and empirical modelling. Practical implications are related to the correct selection of the tool path strategy and feed rate value for machining of thin-walled aluminium components in order to achieve the required output techno-economic effects.

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A R T I C L E I N F O

Keywords:
Thin-walled structures;
Aluminium alloy Al 7075;
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Response surface methodology;
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1. Introduction

Due to its homogeneity, corrosion resistance, and excellent ratio between load capacity and weight, thin-walled aluminium components are increasingly being used as structural parts in the aerospace, automotive, military and other branches of electrical-mechanical industry [1, 2]. New designs of these components are focused on monolithic parts rather than a larger number of components that require to be assembled after machining. In this way, the result is a design with good mechanical characteristics, better quality and accuracy, lower weight and less production time and costs [3]. The design of thin-walled structures can vary from simple line and rectangular form to more complex geometric forms [4].

The manufacturing process of thin-walled parts is mainly performed by removing the material from blanks, in a large percentage from their original volume and mass, making it a time-consuming and challenging process [5, 6]. Consequently, machining demands are directed to high productivity, causing in turn the occurrence of issues related to machining vibrations and elastic deformations of thin-walled structures that affect the surface roughness, as well as dimensional and shape accuracy [7, 8]. In addition to this, permanent deformations of the structure can occur, and this may cause the incidence of rejected parts [9, 10]. Numerous factors of process planning are affected by the aforementioned issues, such as the elements of the machining system (machine tool, tool, and fixture), cutting parameters, tool-path strategy, cutting fluids, etc. [11-14].

In parallel with the increasing market demands for aluminium alloy thin-walled components, there is a number of accomplished researches focused on optimizing the structure in order to reduce mass, deformation, and vibration, i.e. increase load capacity and strength. Also, researches are focused on optimization of process planning of these components aiming to reduce the machining time and costs, and increase the accuracy of shapes and positions, and improving surface roughness, etc. [3, 4, 15, 16].

Novak-Marcincin *et al.* [17] investigated the possibility of a quick analysis of the appropriate tool path in the process of milling different features (rectangle, circle, L-shape and T-shape). Based on the obtained results, a software solution is developed to assist in the selection of optimal milling strategy on the basis of the minimal processing time. Pandian *et al.* [18] analysed the influence of the cutting forces on the deformation during the machining of thin-walled parts which results in different wall thickness, larger at the top and smaller in the root. Authors applied the developed Artificial Neural Network (ANN) and Particle Swarm Optimization (PSO) for prediction of the cutting force during machining of thin-walled parts. Msaddek *et al.* [19] represented the methodology for the optimization of machining strategies implemented for machining complex shaped pockets. For this purpose, authors developed the analytical model which is used for modelling feed rate value regarding the tool path strategy. Denkena and Schmidt [20] defined an improved simulation model which predicts a form of unsuitable deviation occurring during the milling of the ends of thin-walled structures. Their paper analyses the effect of cutting forces that causes the deflection of thin-walled structures and the occurrence of errors on machined parts. Peripheral milling of thin-walled structures is modelled in Budak and Altintas [21]. The developed model provides satisfactory predictions of cutting forces and dimensional surface defects throughout the deflection of cutting tool and thin-walled structures during the milling process. Baranek *et al.* [22] emphasized the influence of material removal on the surface roughness of thin-walled structures during the milling process. Experimental research on the stability of milling the thin-walled aluminium structure, as well as the measurement of cutting forces and acceleration, was conducted in Rusinek *et al.* [23]. The analysis was performed through the stability diagrams and recurrent quantification analysis. Kanchana *et al.* [24] used the finite elements method approach and the analysis of frequency response for machining of thin-walled components for aerospace industry purposes. Arnaud *et al.* [25] investigated the stability of machining the thin-walled aluminium structures. The system was modelled using a dynamic mechanistic model, while the dynamic system parameters were obtained using the finite element analysis. Masmali and Mathew were used an analytical approach to predict dynamic chip thickness variation during machining of thin wall workpieces [26]. Pare *et al.* [27] implemented metaheuristic methods for selecting optimum process parameters in high speed CNC end-milling of composite materials. They compared Gravitational Search Algorithms (GSA) with Genetic Algorithm (GA), Simulated Annealing (SA) and Teaching-Learning-Based Optimization (TLBO) methods. Ratchev *et al.* [28] represented a virtual environment for the simulation and prediction of the deviation of the thin-walled structures during the machining process. The model for material removal was based on an iterative voxel transformation algorithm.

Taking into consideration the conclusion from listed literature above, it can be concluded that the field of machining the thin-walled structures has been the research subject around the world for many years now. It was identified that there is no universal model or unique approach that could be implemented in this field. The aforementioned researchers were oriented to individual input/output parameters of process plan for the machining of thin-walled parts, with different techniques applied, such as simulation methods and models, predictive models, stability diagrams, finite element method, and so on. The main goal in this research relates to the development of the methodology for optimization of machining parameters for thin-walled structures. In this way, the focus is put on the improvement of process planning function which currently represents a bottleneck in the production environment, and the integration of product design and manufacturing. The methodology is based on the simplicity and generality of application with a quick and easy way of reaching reliable data for the process planning for machining of thin-walled parts. It can easily be applied to other shapes of thin-walled structures, other materials, with the inclusion of other input/output parameters of machining process.

The primary hypothesis of this research was that the change of a tool path strategy and cutting conditions of aluminium alloy thin-walled structures affects the machining time, surface roughness and dimensional, shape and position accuracy of workpieces. According to the given hypotheses, the aim of this research was focused on the selection of an optimal tool path strategy, wall thickness and feed rate value of line type aluminium thin-walled structures for the best machining responses. The target responses which were selected include: the shorter machining time, the smallest wall thickness, perpendicularity, flatness deviation and the smallest surface roughness.

2. Materials and methods

Optimization theory as a scientific discipline is more frequently used in solving engineering problems, where, on the basis of criteria and the appropriate optimization method, the best solution is being found for a selected object of the optimization in line with machining requirements. The main phases in the proposed experimental procedure of the process parameters optimization methodology for the machining of aluminium alloy thin-walled structures are shown in Fig. 1 and described below. Optimization methodology was performed using ANOVA method within Design Expert Software [29].

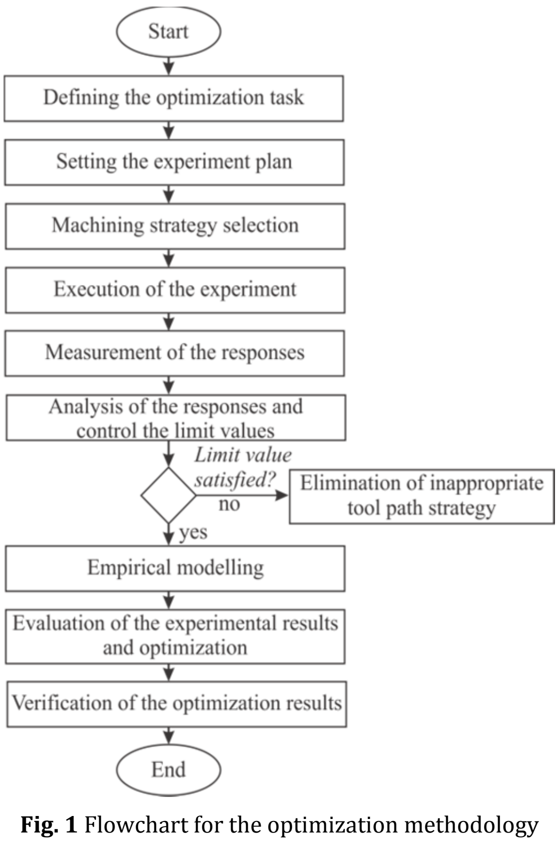


Fig. 1 Flowchart for the optimization methodology

2.1 Defining the optimization task

The object of the research was the line-type aluminium alloy thin-walled structure machining, having wall thickness a from 0.5 mm to 1.5 mm, which is moderately low compared to wall height L (L:a = 30:1).

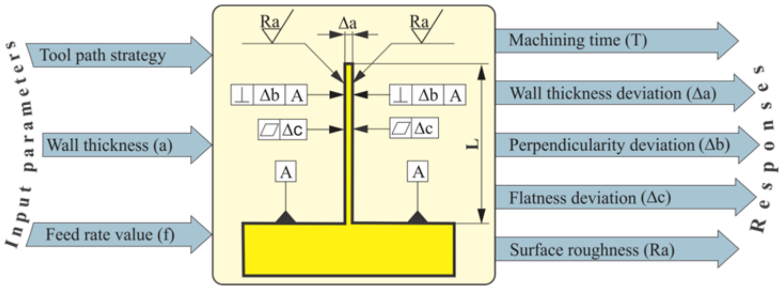


Fig. 2 Scheme of input parameters and responses

Basic optimization task refers to the determination of the influence of tool path strategy, wall thickness *a* and feed rate value *f* on machining time *T*, wall thickness deviation *Δa*, perpendicularity deviation *Δb,* flatness deviation *Δc*, as well as surface roughness *Ra*. This task was solved using the experimental optimization method, which scheme is shown in Fig. 2. The parameters *T, Δa, Δb, Δc* and *Ra* can be observed as measured outputs, i.e. responses.

2.2 Setting the experimental plan

The stage of setting the experimental plan was carried out using the Design-Expert Software. The software supports a large number of experimental designs, while for the present case the Central Composite Design was selected. Three factors, two numerical and one categorical all on three levels generated the total of 33 experiments. The first numerical factor was the thickness of the line-type thin-walled structure *a*, with the lowest limit of 0.5 mm, and the highest limit value of 1.5 mm. Second numerical factor was milling feed rate *f*, with the lowest limit at 150 mm/min, and the highest limit value at 350 mm/min. For the third, categorical factor, three different tool path strategies were chosen. Tool path strategies for machining the thin-walled structures were selected based on the recommendations from the literature [4, 18, 21]. These tool path strategies are as follows:

- Tool path strategy No. 1 (Parallel spiral) 
- Tool path strategy No. 2 (Zigzag) 
- Tool path strategy No. 3 (True spiral) 

2.3 Machining strategy selection

This phase encompasses the selection of the machining strategy in the terms of machining passes sequencing during machining process of thin-walled structures. Selected machining passes sequence for this experiment was adopted from [30]. Selected machining passes sequence implies that the first machining pass was executed at the left side of thin-walled structure, then the second and the third machining pass were executed at the right side of thin-walled structure. Next, the fourth and the fifth were executed again at the left side, and so on up to the twentieth pass at the bottom of the structure as shown in Fig. 3. Machining of thin-walled structure was performed with the following fixed parameters: depth of cut a_p = 3 mm, step over distance a_e = 8 mm for each machining pass and spindle speed n = 2000 min^{-1}.

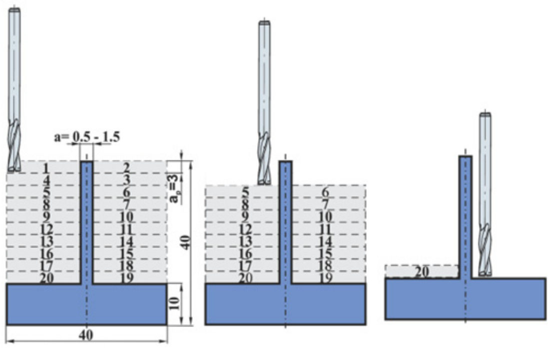


Fig. 3 Selected machining passes sequence for the machining of thin-walled structures

2.4 Experimental procedures

Realization of the experiments

Block samples (33 pieces) with dimensions of 70×40×40 mm from Al 7075 alloy (AlZnMgCu1.5) were chosen and prepared. This Al-alloy has very good mechanical properties, as well as high resistance to fatigue and corrosion, which makes it suitable for use in the milling of thin-walled structures. The chemical composition of this alloy is Al (87.1–91.4 %), Cr (0.18–0.28 %), Cu (1.2–2 %), Fe (≤0.5 %), Mg (2.1–2.9 %), Mn (≤0.3 %), Si (≤0.4 %), Ti (≤0.2 %), Zn (5.1–6.1%). Basic mechanical characteristics are: tensile strength (560 MPa), $Rp_{0.2}$ (500 MPa), yield strength (7 %), and hardness (150 HBW).

CNC machining centre – EMCO Concept Mill 450, and the milling cutters with the identification R216.32-10025-AK32 from the Sandvik Coromant were used for the realization of the experiments. The positioning and clamping of the samples in the milling process were carried out using a pneumatic clamp with pre-set limiter.

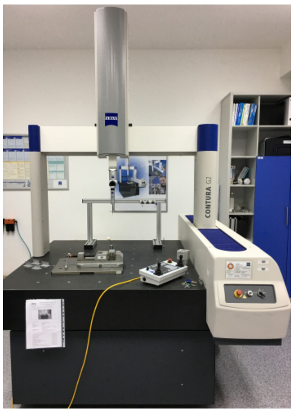
Measuring of the responses

According to the experiment plan, the following responses of the thin wall structure machining process were measured:

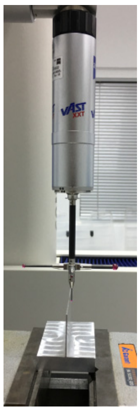
- Machining time – T,
- Wall thickness deviation – Δa,
- Perpendicularity deviation – Δb,
- Flatness deviation – Δc,
- Surface roughness – Ra.

The measurements of the dimensional parameters were performed using the coordinate measurement machine Zeiss Contura G2 (Fig. 4a) together with sensor touch probe Zeiss Vast XXT shown in Fig. 4b. The Maximum Permissible Error MPE = 1.9 μm for size measurement according to ISO 10360-2:2009 is specified for this machine.

Surface roughness measurements were conducted with the INNOVATEST contact device, in direction perpendicular to the cutter movement on both sides of the wall. The device has the ability of measuring the parameters Ra and Rz. The roughness measurements were performed with a stylus radius of 2 μm and resolution of 0.01 μm.



a)



b)

Fig. 4 Measuring of parameters Δa, Δb and Δc on machined parts by CMM

Analysis of the responses and control of the limit values

At this phase, the intervals of responses values obtained from the measurements of all three tool-path strategies were analysed (Fig. 5). Limit values of responses were predefined as follows: maximal wall thickness deviation $max\Delta a$ = 0.2 mm, maximal perpendicularity deviation $max\Delta b$ = 0.1 mm, maximal flatness deviation $max\Delta c$ = 0.1 mm and maximal surface roughness *maxRa* = 1.6 µm. The analysis of the limit value intervals of all responses shows that the values of wall thickness deviation Δa, perpendicularity deviation Δb, flatness deviation Δc and surface roughness Ra for tool path strategy No. 2 do not fall into the predefined limit values, causing the tool path strategy No. 2 to be excluded from further research. Tool path strategies No. 1 and No. 3 satisfied the limit values, and therefore both were taken into consideration for determining the optimal strategy.

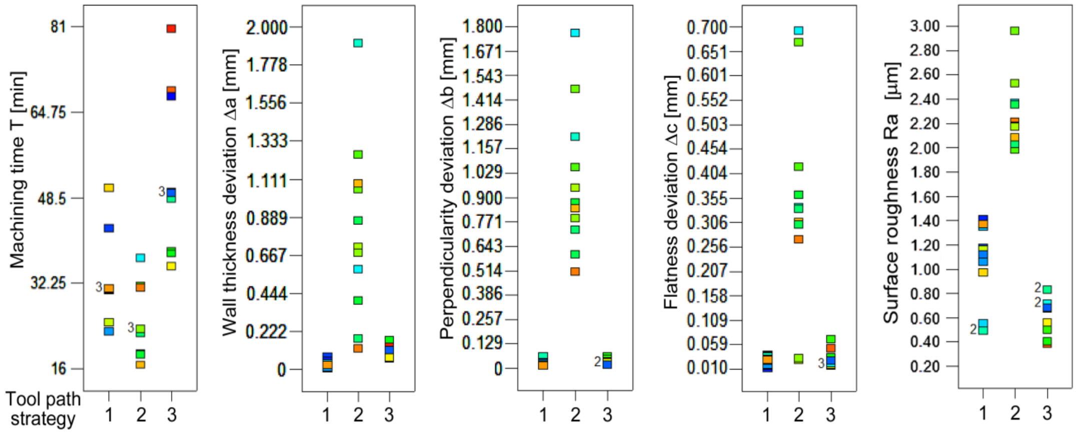


Fig. 5 Intervals of the values *T, Δa, Δb, Δc* and *Ra*

3. Results and discussion

3.1 Empirical modelling

After manual elimination of inadequate tool path strategy No. 2, responses of both other strategies, No. 1 and No. 3 were empirically modelled. Results from this stage are empirical models of responses for both tool path strategies, which are listed in Table 1. All models were obtained using quadratic polynomial modelling with some transformations for better model results.

Table 1 Empirical models of responses

Tool path	Empirical model	Responses
No. 1	$lnT = 4.89861 + 2.14456 \cdot 10^{-3} \cdot a - 7.7971 \cdot 10^{-3} \cdot f + 7.84629 \cdot 10^{-6} \cdot f^2$	Machining time
No. 1	$\sqrt{\Delta a} = 0.66044 - 0.32615 \cdot a - 2.34118 \cdot 10^{-3} \cdot f + 1.68538 \cdot 10^{-3} \cdot a \cdot f$	Wall thickness deviation
No. 1	$ln\Delta b = 1.51485 - 5.24519 \cdot a - 0.020474 \cdot f + 2.29188 \cdot a^2 + 4.12498 \cdot 10^{-5} \cdot f^2$	Perpendicularity deviation
No. 1	$\frac{1}{\sqrt{\Delta c}} = 3.20174 + 3.36622 \cdot a$	Flatness deviation
No. 1	$\sqrt{Ra} = -0.80634 + 1.80076 \cdot a + 5.71813 \cdot 10^{-3} \cdot f - 1.67948 \cdot 10^{-3} \cdot a \cdot f - 0.44182 \cdot a^2 - 8.04146 \cdot 10^{-6} \cdot f^2$	Surface roughness
No. 3	$lnT = 5.437 - 0.02208 \cdot a - 8.04091 \cdot 10^{-3} \cdot f + 7.84629 \cdot 10^{-6} \cdot f^2$	Machining time
No. 3	$\sqrt{\Delta a} = 0.85989 - 0.44928 \cdot a - 1.96566 \cdot 10^{-3} \cdot f + 1.68538 \cdot 10^{-3} \cdot a \cdot f$	Wall thickness deviation
No. 3	$ln\Delta b = 1.70287 - 5.24519 \cdot a - 0.020474 \cdot f + 2.29188 \cdot a^2 + 4.12498 \cdot 10^{-5} \cdot f^2$	Perpendicularity deviation
No. 3	$\frac{1}{\sqrt{\Delta c}} = 2.52262 + 3.74762 \cdot a$	Flatness deviation
No. 3	$\sqrt{Ra} = -0.78597 + 1.57972 \cdot a + 5.71813 \cdot 10^{-3} \cdot f - 1.67948 \cdot 10^{-3} \cdot a \cdot f - 0.44182 \cdot a^2 - 8.04146 \cdot 10^{-6} \cdot f^2$	Surface roughness

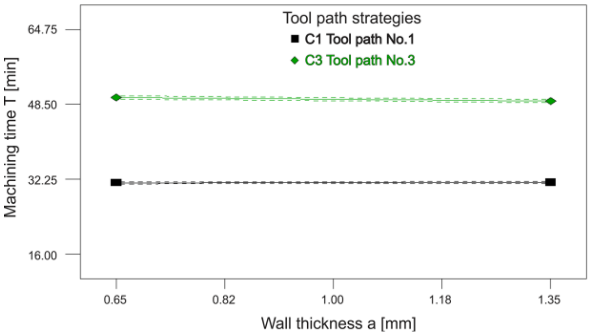


Fig. 6 Machining time T for tool paths

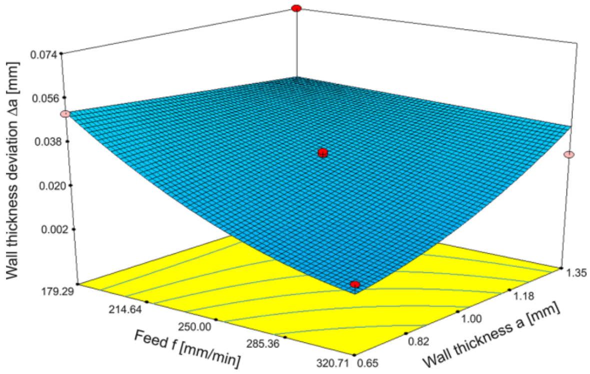


Fig. 7 3D surface diagram for the thickness deviation Δa with tool path strategy No. 1

Based on the carried experiments and empirical modelling, graphical results, i.e. 3D surface diagrams were obtained and discussed below.

As it is well-known, machining time is influenced by feed rate value. While wall thickness, on the other hand, does not show almost any significance on machining time. This refers to both tool path strategies. It was recorded that machining time for tool path strategy No. 1 was significantly shorter than for No. 3 for same feed rate values f, as can be seen in Fig. 6.

The influence of feed rate f and wall thickness a on wall thickness deviation Δa for tool path strategy No. 1 is shown in 3D surface diagram in Fig. 7. It can be seen that maximum wall thickness deviation for this tool path strategy was lower than 0.05 mm.

Wall thickness deviation decreases with higher feed rates. Model also shows that wall thickness deviation is proportional to the wall thickness, and that with the higher wall thicknesses, feed rate has almost no influence on wall thickness deviation.

3D surface diagram for wall thickness deviation Δa using tool path strategy No. 3 is shown in Fig. 8. In this case maximum wall thickness deviation of 0.17 mm and min. deviation of 0.08 mm was achieved. Wall thickness deviation for tool path strategy No. 3 is also strongly influenced by feed rate with lower wall thickness, while less influence of feed rate is noticed with higher wall thickness. It can be seen that tool path strategy No. 1 gives much better results when thickness deviation is considered.

3D surface diagram for the perpendicularity deviation Δb using tool path strategy No. 1 is shown in Fig. 9. Models for perpendicularity deviation Δb for both tool path strategies show the same trends, i.e. perpendicularity deviation rises with wall thickness reduction, while feed rate does not have significant influence. Best results, i.e. the lowest deviation can be achieved with middle values of feed rate. Maximum perpendicularity deviation Δb for tool path strategies No. 1 of 0.04 mm is predicted and it is lower than for tool path strategies No. 3 (0.05 mm).

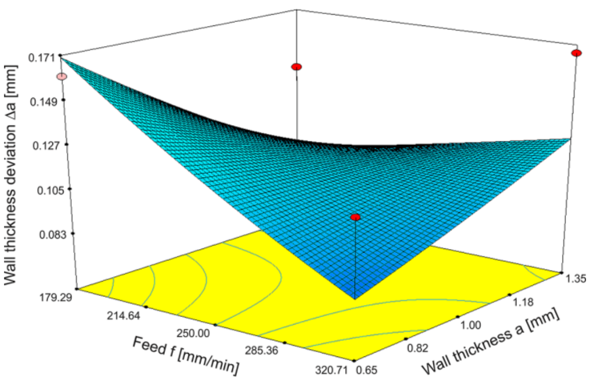


Fig. 8 3D surface diagram for the thickness deviation Δa with tool path strategy No. 3

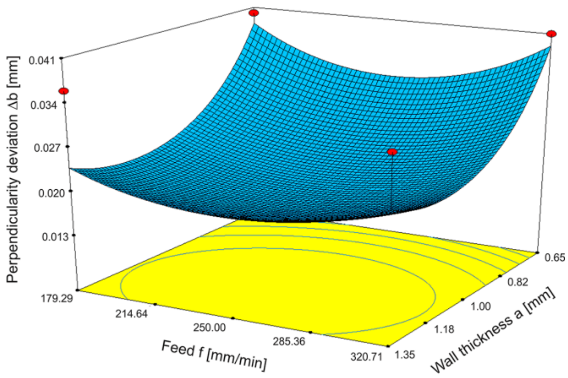


Fig. 9 3D surface diagram for the perpendicularity deviation Δb with tool path strategy No. 1

Influence of feed rate and wall thickness on flatness deviation Δc for tool path strategy No. 1 is shown by 3D surface diagram in Fig. 10. Flatness deviation for both tool path strategies (No. 1 and No. 3) shows the same dependence, i.e. flatness deviation is significantly influenced by wall thickness, while feed rate almost does not have any influence.

Flatness deviation is inversely proportional with wall thickness. Maximum flatness deviation Δc for tool path strategies No. 1 has value of 0.035 mm and it was just a bit lower than for the tool path strategies No. 3 (0.04 mm), both for the same wall thickness a = 0.65 mm.

3D surface diagram for the surface roughness Ra for tool path strategy No. 3 is shown in Fig. 11. Also in this case, surface roughness models for both tool path strategies show the same dependence, i.e. surface roughness is proportional to the wall thickness, while feed rate affects roughness inversely proportionally only with higher wall thicknesses. Maximum surface roughness achieved with tool path strategy No. 1 was Ra = 1.41 μm and it was higher than for tool path strategy No. 3 (Ra = 0.83 μm).

Taking into consideration empirical models and 3D surface diagrams, it can be concluded that tool path strategy No. 1 has advantages over tool path strategy No. 3 in the following responses: machining time, thickness deviation, perpendicularity deviation and flatness deviation. Tool path strategy No. 3 has only an advantage in surface roughness. Based on these reasons, tool path strategy No. 1 can be declared as the one which generates the best responses for previously adopted conditions of experiment. For those reasons, the optimization of process parameters for thin wall structures machining was executed only for tool path strategy No. 1, i.e. parallel spiral.

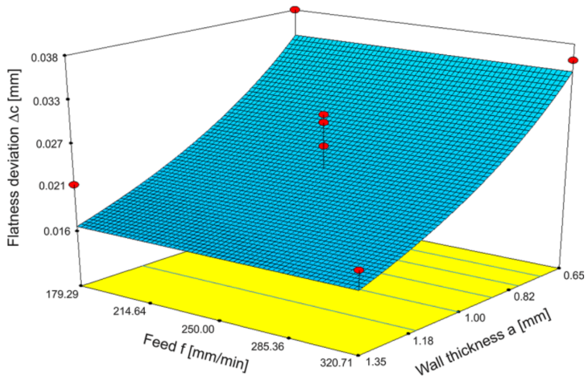


Fig. 10 3D surface diagram for the flatness deviation Δc with tool path strategy No. 1

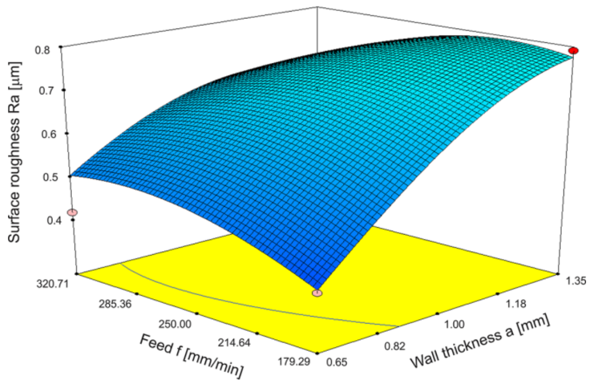


Fig. 11 3D surface diagram for the surface roughness Ra with tool path strategy No. 3

3.2 Evaluation of the experimental results and optimization

Empirical models were then used for machining optimization. As concluded above, the optimization of machining parameters was performed for the tool path strategy No. 1 only. The main objective of optimization was the selection of optimal feed rate values for specific wall thickness between 0.5 mm and 1.5 mm, using the step of 0.1 mm, which would generate the smallest values of responses, i.e. the smallest deviation in thin wall structure machining.

Criteria and goals of optimization process are given in Table 2. As it can be seen, the highest weight coefficient was assigned to wall thickness deviation, because the scope of the experiment was related to machining of thin wall structures, where the main geometrical feature of thin wall structure is its thickness. Other weight coefficients have the same values i.e. other responses have the same level of importance.

The optimal feed rate values for different wall thickness values and corresponding predicted values of responses for the tool path strategy No. 1 are shown in Table 3. Results show that except for the thickest wall, the feed rate should be set at maximum value f = 350 mm/min.

Table 2 Criteria and goals of optimization process

Responses	Goal	Lowest limit	Highest limit	Weights
Wall thickness	Equal to specific value	0.5	1.5	1
Feed rate	in range	150	350	1
Machining time	minimize	10	90	1
Thickness deviation	minimize	0.005	1	10
Perpendicularity deviation	minimize	0.01	1.85	1
Flatness deviation	minimize	0.01	0.7	1
Surface roughness	minimize	0.2	3,2	1

Table 3 The optimal parameter settings and predicted responses for different wall thickness (tool path strategy No. 1)

a [mm]	f [mm/min]	T [min]	Δa [mm]	Δb [mm]	Δc [mm]	Ra [µm]
0.5	350	22.9	0.07	0.042	0.05	0.76
0.6	350	22.9	0.054	0.037	0.06	0.77
0.7	350	22.9	0.001	0.043	0.03	0.7
0.8	350	22.9	0.003	0.036	0.029	0.8
0.9	350	22.9	0.006	0.031	0.026	0.9
1	350	22.9	0.011	0.029	0.023	1.0
1.1	350	22.9	0.017	0.027	0.021	1.0
1.2	350	22.9	0.025	0.028	0.019	1.1
1.3	350	23	0.034	0.029	0.017	1.1
1.4	350	23	0.044	0.032	0.016	1.1
1.5	293	23	0.056	0.037	0.015	1.1

3.3 Verification of the optimization results

The verification of optimization results were conducted on two samples with wall thickness of a = 0.7 mm and a = 1.2 mm. Feed rate f was set according to the optimization at 350 mm/min and tool path strategy No.1 was selected. The other cutting conditions of experiments were kept the same as in the main experiment. After machining of the samples, the process of measurement of responses was conducted in the same manner and with the same equipment.

Verification results are shown in Table 4. It can be seen that results of verification tests deviate from the predicted values for less than 10 %. These results can be accepted as satisfactory, considering the complexity of the machining process of thin-walled structures, the conditions of machining, machine rigidity, the occurrence of vibration, and other influencing factors.

Table 4 Results of verification test

Sample	Tool path strategy	a [mm]	f [mm/min]		T [min]	Δa [mm]	Δb [mm]	Δc [mm]	Ra [µm]
1	1	0.7	350	Predicted value	22.9	0.001	0.043	0.03	0.7
2	1	1.2	350		22.9	0.025	0.028	0.019	1.1
1	1	0.7	350	Measured values	23	0.001	0.041	0.033	0.76
2	1	1.2	350		23.3	0.027	0.027	0.020	1.18
1	1	0.7	350	Deviations of values	0.4 %	0 %	4.6 %	10 %	8.5 %
2	1	1.2	350		1.7 %	8 %	3.6 %	5.3 %	7.2 %

4. Conclusion

The optimization methodology for thin wall structures machining was presented in this research. Significant savings in machining time were achieved by selecting the optimal tool path strategy and feed rate value, and at the same time meeting the quality factors (i.e. responses) in terms of accuracy of wall thickness deviation, perpendicularity deviation, flatness deviation and surface roughness. The determined tool path strategy and feed rate value are suitable for machining the line-type aluminium alloy thin-walled structures. They are also suitable for structures with similar configuration, such as the rectangular-type structures.

Based on these results, it can be concluded that the tool path strategy No. 1, i.e. parallel spiral provides the most satisfactory response values for wall thickness from 0.5 mm up to 1.5 mm. It is also important to highlight the significance of generated empirical models, which give insights into machining process within the considered research.

The verification of the optimization results shows the maximum deviation of 10 % in measured and predicted values, which represents a significant achievement in the field of thin-walled structures machining. The obtained results confirmed the defined research hypotheses. The represented methodology gives reliable data on the input/output parameters of machining process, which can be used for developing a knowledge base within the process planning system. It was proved that the optimization of machining parameters has an influence on improving the manufacturing of thin-walled components, primarily in terms of machining time, machining accuracy and quality itself.

In addition to the presented technological effects, realized optimization has a significant impact on the economic effects, which are easily recognizable here. Based on obtained results, it can be seen that the main machining time for the tool path strategy No. 1 is shorter than the machining time for tool path strategy No. 3, thereby it affects the increase of the manufacturing productivity. On the other hand, using the proposed optimization methodology, it is easy to identify the values of the input parameters that provide the required parameters of accuracy and surface quality. This reduces the possibility of scrapping and additional milling operations, which results in a reduction of production costs.

In order to obtain the generality of the optimization methodology for thin-walled structures process planning, it is necessary to expand the research to other shapes, such as triangular, hexagonal and other more complex shapes.

Researching should also be expanded on machining of other light alloys and composites, as well as thin-walled structures with wall thickness up to 3 mm, and larger height-to-thickness ratio (> 30:1). Monitoring of the cutting forces, occurrence of vibrations in machining and possible deformations of workpiece structures should be taken into consideration as well.

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Multi-criteria blocking flow shop scheduling problems: Formulation and performance analysis

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A B S T R A C T

Most of the prior investigations related to production scheduling problems have solely focused on the optimization of an individual criterion under a single constraint; nevertheless, this is most of the time out of true in a real situation. This paper deals with multi machines permutation flow shop scheduling with limited buffers capacity and different release dates of jobs, where the performance is measured by the minimization of the weighted sum of maximum tardiness and makespan. To tackle this NP-hard problem, we present a mixed-integer linear programming model (MILP). Thereafter, using CPLEX software, we generate a set of tests in an endeavor to examine formulation for dissimilar size problems in terms of optimality solution and computational CPU time complexity. Experiment results show that overall the proposed model is computationally avaricious to solve the considering problem.

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A R T I C L E I N F O

Keywords:
Permutation flow shop scheduling;
Tardiness;
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1. Introduction

Scheduling is a technique of decision-making that greatly affects the ability to reach the success of the organizations, by drawing up a detailed operational plan, company can establish a mandate and adopt a process that will allow it to maintain the desired level of customer service, make the best use of resources, and subsequently, minimize costs and maximize profit. The core motor of this operational plan is to find the best schedule that will achieve an adequacy between a job to be performed and the resources available for its realization, in the most effective way. In fact, owing to the unpredictability of the production systems that are organized in workshops, jobs are often executed according to temporal and technological constraints.

On that account, the resolution of permutation flow shop scheduling problems (PFSP) is a longstanding challenge that has been widely studied over the last decades; this basic scheduling environment is portrayed by a set of n jobs, which are to be performed sequentially, by a set of m serial machines system in the same permutation. Henceforth, the processing steps are identical for all the manufactured products and the storage capacity buffers is limited. The case of limited storage capacity is of greatest interest as the majority of research allows at least some storage. However, limited capacity buffers give subsequently rise to situations that are known in the literature as blocking flow shop scheduling problems (BFSP). In this circumstance, a job cannot leave a machine unless the next downstream machine is available for processing. This blocking restriction appointed as a release when starting blocking (RSB) describes one of the precedence relations, which can exist between the different structures.

Following the standard three-field notation of [1], the bicriteria m-machines BFSP with different release dates of jobs taking into account the maximum tardiness and makespan criteria is denoted as $F_m|block, r_k|C_{max}, T_{max}$. If works carried out till now have proven that BFSP with more than two machines is strongly NP-hard, when the makespan $C_{max}$is a measure of performance, it can be obviously inferred that the considered problem cannot be solved optimally in $O(n \log n)$.

However, a great deal of studies have been developed touching the approaches of resolution of the scheduling problems, ranging from the branch-and-bound algorithm that appear to be effective to erect exact methods in view of the considered problem complexity [2], into the heuristics aiming at obtaining approximate solutions in a reasonable calculation time [3]. In this context, concerning the RSB constraint, Trabelsi [4] proposed exact methods, approached methods and lower bound in order to determinate the best schedule reducing makespan under mixed blocking constraint for the BFSP and its extension. Wang *et al.* [5] developed a hybrid genetic algorithm for blocking flow shop scheduling problem. Tasgetiren *et al.* [6] presented iterated greedy algorithms for solving the BFSP with the makespan criterion. Sadaqua and Moraga [7] suggested meta-heuristic for randomized priority search (Meta-RaPS) to minimize makespan. Another survey is described in [8], in such study, authors proposed a branch-and-bound algorithm to deal with the same problem with total completion time criterion. Eddaly *et al.* [9] suggested a hybrid combinatorial particle swarm optimization algorithm (HCPSO) as a technique of resolution to minimize makespan of BFSP. Thus, regarding the release dates restriction, Ardakan *et al.* [10] studied two machines flow shop scheduling problem with release dates to minimize the number of tardy jobs in a permutation. Moreover, Kalczynski and Kanburowski [11] presented a new heuristic algorithm to solve the identical problem with makespan criterion. Huang *et al.* [12] proposed an improved genetic algorithm for solving JSP based on process sequence flexibility. Xu *et al.* [13] established a mathematical model based on process sequence flexibility and machine selection flexibility, and proposed an improved bat algorithm to solve it.

In an industrial environment, a decision maker often needs to take into account concurrently two or more conflicting criteria. Hence, the multi-objective flow shop scheduling problems have been the subject of extensive studies. Unfortunately, the majority of bicriteria flow shop investigations consider the combination of makespan only with total flow time or with total completion time [14-16]. Very few studies have been related to the minimization of maximum tardiness and makespan as two criteria in flow shop environment. The first being the investigation of [17], wherein the authors presented a branch-and-bound procedure for permutation flow shop with bicriteria of the both considered measure of performance and searched thereafter the set of Pareto optimal. Chakravarthy and Rajendran [18] formulated the same study with the simulated annealing approach. Allahverdi [19] proposed a new heuristic for m-machines flow shop scheduling problems with the objective of minimizing a weighted sum of makespan and maximum tardiness. Recently, Fernandez-Viagas and Framinan [20] have suggested two new non-population-based algorithms for the permutation flow shop scheduling problem to minimize makespan subject to a maximum tardiness. In contrast, research works, in this field, are more than welcome.

As well as, mixed-integer linear programming (MILP) represents one of detailed mathematical statement mostly used for proving the optimality status of the current master problem solution. It is based on the fact that only some of the variables are constrained to be integers, while other variables are allowed to be non-integers. Using some specific optimization software, e.g., (CPLEX, M-XPRESS, LINGO, and Lp-solve), efficient solution relative to the aforementioned mathematical formulation can be obtained for different size problems. Great effort has been devoted to the study of MILP flow shop models. The most comprehensive and interesting is that of [21], wherein, the authors discussed the computational performance of two famous families of mixed-integer linear programming models for solving the regular permutation flow shop problems with makespan criterion. Similarly, Ranconi and Bergin [22] have evaluated mixed-integer linear programming formulations for a flow shop environment with finite and infinite storage capacity, with the aim to minimize the total earliness and tardiness. In [23], authors have provided a detailed mixed-integer model for a flow shop with mixed blocking. Moreover, Moslehi and Khorasanian [8] have presented two mixed binary integer programming models, one of which is based on the departure times of jobs from machines, and the other on the idle and blocking times of jobs

As can be seen from the above, the problem of $F_m|block, r_k|C_{max}, T_{max}$ has not been discussed with any exact or meta-heuristic method in the literature thus far. In fact, our contribution aims to propose and assess the computational performance of MILP model for multi-machines BFSP with release dates of jobs, where the objective is to minimize the weighted sum of maximum tardiness and makespan.

The remainder of the paper is organized as follows. In Section 2, the definition of the problem under study, the formulation of the proposed mixed integer linear programming and the adopted method for identifying the efficient frontier of the bicriteria model are presented. Section 3 is devoted to test problems, experiments and the computational results. Finally, conclusions and suggestions for future research areas are provided in Section 4.

2. Problem formulation and used methods

2.1 The multi-objective blocking flow shop scheduling problems under r_k constraint

The problem $F_m|block, r_k|C_{max}, T_{max}$ consists of a finite set $(J_1, \dots, J_n)$ of jobs which are to be performed sequentially on a set $(M_1, \dots, M_m)$ of machines in the same routing of process, i.e., sequence of job in all the machines system is identical, thus characterizing a permutation flow shop scheduling problem. Further, each job is composed of $(O_{k1}, \dots, O_{km})$ constructive operations O_{ki}, where, each operation has a positive integer running time equal to P_{ki} , each job has a due date d_k, and an integer release dates r_k for which it becomes available and ready for processing. It is assumed that there is no capacity buffers between machines and the job of each machine remains blocked until the next downstream machine is free. At each time, each job can be performed solely on one machine and each machine can process only one job at the time. Eventually, the setup times are included in the routing times of operations and the process cannot be interrupted at any time, to be resumed later on another machine. It is presumed that there is no idle time on machine 1, and there is no blocking time on the last machine.

In order to illustrate the BFSP with different release dates of jobs, an example is provided in Fig. 1, it exemplifies a simple case of the afore-mentioned snag, where three machines and four jobs are considered. Further, given a processing sequence P = (J_1, J_2, J_3, J_4), the running times of jobs on machines and other required data are summarized in Table 1.

From the above example, it can be sighted that there is an RSB constraint between machine 1 and machine 2, therefore, machine 1 rests blocked by a job 2 until job 1 finishes processing in the second machine. The example shows also, that there is an intermediate idle time between jobs 2 and 3 processed by machines 2 and 3, respectively. Besides, even if the first machine becomes free after blocking, it can be observed that, there in a non- productive times during which jobs are not ready for processing due to their release dates that must be respected. Hence, taking into account the date of availability of each job in the first machine must be considered foremost.

Table 1 Example data

Machines \ Jobs	1	2	3	4
1	1	3	6	2
2	4	2	2	3
3	2	1	3	2
Release dates	2	3	8	4

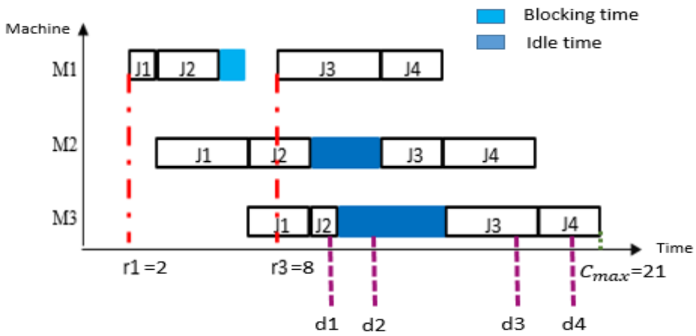

Fig. 1 Gantt chart of BFSP example with different release dates

The target of this study is to obtain the topper schedule, which minimizes the weighted sum of maximum tardiness, and makespan, respectively. According to [17], those scheduling criteria of interest can be formulated as follows:

$$C_{max} = \max_{j\in[1....n]} C_{jm} \tag{1}$$

$$T_{max} = \max_{j\in[1....n]} T_{jm} \tag{2}$$

where, $j = 1, \ldots, n$, m is the last machine in the production system. C_{jm} is a completion time of job j on the machine m and $T_{jm} = \max(C_{jm} - d_k, 0)$ represents the tardiness of job j.

The weighted objective function method allows identifying the efficient frontier for the multicriteria problem. This intuitive technique is most broadly used given its relevance proficiency regarding the convex problems, for which, it guarantees to find solutions on the entire Pareto-optimal set. Thereby, the aim is to return to a mono-objective problem of optimization, for which there exist several methods of resolution. The simplest way is to assign to each objective function $f_i(x), i = 1, \ldots, p$, an appropriate user-supplied weight factor w_i according to the relative importance of each objective, so as to, obtain an aggregated scalar objective function. The product that provides the scalar objective $F(x, w)$ can be posed as follows:

$$F(x, w) = \sum_{i=1}^{p} w_i f_i(x) \tag{3}$$

That is, $\sum_{i=1}^{p} w_i = 1$ and $w_i > 0$, these values have to be normalized if the scales and units of the objectives are different as reported by [22], also they cannot be equal to 0, in order that the set of solutions does not occur narrow Pareto optimality.

Since the scales and the units of our considered criteria scheduling are similar. The weights have no to be normalized. Consequently, the objective function of the problem under study may be computed as:

$$Z = \alpha\, C_{max} + \beta\, T_{max} \tag{4}$$

Where, α and β are the weights factors of makespan and maximum tardiness. As long as, $\alpha, \beta > 0$ and α+β=1, the objective function can then be expressed in the following way:

$$Z = \alpha(\max_{j\in[1....n]} C_{jm}) + (1-\alpha)\max(\max_{j\in[1....n]}(C_{jm} - d_k, 0)) \tag{5}$$

2.2 The proposed mathematical formulation

In this section, a mixed-integer linear programming model for the $F_m|block, r_k|C_{max}, T_{max}$ problem is formulated. With the addition of the release dates of jobs constraint, this model is inspired from the models presented in [23]. We have adapted our model to consider the different constraints and the measures of performance afore-mentioned at the same time. Indices, parameters and variables being using in this formulation are given below.

Indices

k	Job index
i	Machine index
j	Index on the position of job k in sequence P

Parameters

n	Total number of jobs, $k = 1, 2,\ldots, n$
m	Total number of machines, $i = 1,2,\ldots,m$
t_{ki}	Processing time of job k on the *i-th* machine, $k = 1, 2,\ldots,n$, $i = 1, 2,\ldots, m$
D_k	Due date of job k, $k = 1, 2,\ldots, n$
r_k	Release date of job k, $k = 1, 2,\ldots, n$
α	Weight associated with makespan
β	Weight associated with total tardiness
$Z(P)$	Objective value of schedule P
ε_k	$\begin{cases} 1 & \text{If there is a blocking constraint between machine } M_i \text{ and machine } M_{i+1} \\ 0 & \text{Otherwise} \end{cases}$
μ_k	$\begin{cases} 1 & \text{If there is an idle time between machine } M_i \text{ and machine } M_{i+1} \\ 0 & \text{Otherwise} \end{cases}$
θ_k	$\begin{cases} 1 & \text{If there is no blocking constraint and no idle time} \\ 0 & \text{Otherwise} \end{cases}$

Variables

H_{ji}	Starting time of job at position j in sequence P on the ith machine
C_{ji}	Completion time of job at position j in sequence P on the ith machine
x_{kj}	$\begin{cases} 1 & \text{If job } k \text{ is at position } j \text{ in the sequence } P \\ 0 & \text{Otherwise} \end{cases}$

The MILP model

For the modelization of the $F_m|block, r_k|C_{max}, T_{max}$ problem, the $\mu_k, \varepsilon_k, \theta_k$ and x_{kj} are binary parameters and variables, the others are given as integer values. The mixed-integer linear programming MILP is provided as follows:

$$\text{Min} \quad Z(p) = \alpha \; Cmax + (1-\alpha)\, Tmax \qquad \alpha > 0 \tag{6}$$

subject to

$$\textstyle\sum_{k=1}^{n} x_{kj} = 1 \quad \forall\, j \in \{1 \ldots n\} \tag{7}$$

$$\textstyle\sum_{j=1}^{m} x_{kj} = 1 \quad \forall\, k \in \{1 \ldots n\} \tag{8}$$

$$Cmax \geq C_{jm} \quad \forall\, j \in \{1 \ldots n\} \tag{9}$$

$$Tmax \geq C_{jm} - \textstyle\sum_{k=1}^{n} x_{kj}\, D_k \quad \forall\, j \in \{1 \ldots n\} \tag{10}$$

$$H_{j1} \geq \textstyle\sum_{k=1}^{n} r_k\, x_{kj} \quad \forall\, j \in \{1 \ldots n\} \tag{11}$$

$$H_{ji} \geq H_{j-1,i} + \sum_{k=1}^{n} t_{ki}\, x_{kj} \;\; \forall\, j \in \{2 \ldots n\} \;\; \forall\, i \in \{1 \ldots m\} \tag{12}$$

$$H_{ji} \geq H_{j,i-1} + \sum_{k=1}^{n} t_{ki-1}\, x_{kj} \;\; \forall\, j \in \{1 \ldots n\} \;\; \forall\, i \in \{2 \ldots m\} \tag{13}$$

$$H_{ji} \geq H_{j-1,i+1} \quad \forall\, j \in \{2 \ldots n\} \;\; \forall\, i \in \{2 \ldots m\} \tag{14}$$

$$H_{ji} \geq C_{j-1,i}\theta_k + H_{j-1,i+1}\, \varepsilon_k + C_{j,i-1}\, \mu_k \quad \forall\, j \in \{2 \ldots n\} \;\; \forall\, i \in \{2 \ldots m\} \tag{15}$$

$$C_{j1} \geq \sum_{k=1}^{n} r_k\, x_{kj} + \sum_{k=1}^{n} t_{k1}\, x_{kj} \quad \forall\, j \in \{1 \ldots n\} \tag{16}$$

$$C_{ji} \geq H_{ji} + \sum_{k=1}^{n} t_{ki}\, x_{kj} \quad \forall\, j \in \{1 \ldots n\} \tag{17}$$

$$C_{jm} \geq H_{jm} + \sum_{k=1}^{n} t_{ki}\, x_{kj} \quad \forall\, j \in \{1 \ldots n\} \tag{18}$$

$$x_{kj} \epsilon \{0,1\} \quad \forall\, k \in \{1 \ldots . n\} \, \forall\, j \in \{1 \ldots n\} \tag{19}$$

$$H_{ji} \geq 0 \;\; \forall\, j \in \{1 \ldots . n\} \quad \forall\, i \in \{1 \ldots m\} \tag{20}$$

$$C_{ji} \geq 0 \quad \forall\, \mathrm{j} \in \{1 \ldots . n\} \quad \forall\, \mathrm{i} \in \{1 \ldots m\} \tag{21}$$

The objective function (Eq. 6) considers the minimization of the weighted sum of makespan and maximum tardiness. Constraints set (Eq. 7) ensures that every position of the sequence has to incorporate exactly one job. Constraint set (Eq. 8) shows that each job has to be set in the sequence only one time. Constraint set (Eq. 9) indicates that the makespan must be greater than or equal the maximum completion time on the last machine. The maximum tardiness is calculated in constraint set (Eq. 10). Constraint set (Eq. 11) forces jobs to start the processing after their release times. Constraint set (Eq. 12) states the precedence constraint between two operations that have to be performed by the same machine, i.e., in order that a machine starts the forthcoming operation, the operation in a process must be completed. Constraint set (Eq. 13) gives the precedence constraint between two successive operations of the same job, that is, the job cannot start its operation in the downriver machine until it finishes its operation in the upriver machine. RSB constraint between machine M_i and machine M_{i+1} is modeled in constraint set (Eq. 14). Further, constraint set (Eq. 15) designates that, for each starting time H_{ji}, only one constraint will be active. The constraint set (Eq. 15) calculates the completion time of the job in the first machine taking into account the date of availability of each job. Constraints set (Eq. 17) and (Eq. 18) corresponds to the computation of the completion time of jobs in the machine M_i and the machine M_m, respectively. Moreover, (Eq. 19) mentions that x_{kj} is a boolean variable, it is equivalent to 1 if job j_k is assigned to the *j-th* position of sequence and 0 otherwise. Finally, constraints set (Eq. 20) and (Eq. 21) are the logical constraints that state the non-negativity constraints for the starting and the completion times of job.

2.3 The branch-and-bound algorithm

The branch-and-bound algorithm consists of a systematic enumeration of candidate solutions, each node of the tree corresponds to a subproblem designated to as the search tree created by candidate solution, In each iteration of a B&B algorithm, a node is picked for exploration from the pool of live nodes corresponding to unexplored feasible subproblems using some selection procedures. Before calculating the candidate solution, the branch is investigated against upper and lower bounds, if it cannot produce a fitter solution than the best one found so far by the algorithm, the branch is weeded out. Generally, the algorithm goes through two main steps. In the first, it is a question of separating a set of solutions into subsets; whereas in the second phase, it consists of evaluating the solutions of a subset by increasing the value of the best solution of this subset. The search stops when there is no unexplored parts of the solution space left, and the optimal solution is then the one recorded as current best [24]. The procedure is considered as branching downward as represented in Fig. 2.

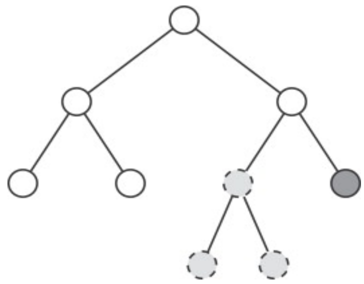

Fig. 2 Branch and bound procedure

3. Results and discussion

3.1 Test problems and experiments

In order to assess the computational behavior of the proposed MILP model, difficult problem instances should be considered. As a matter of fact, problem size was varied with the instances mentioned bellow.

$$(n, m) = \{(10,7), (10,10), (15,3), (15,7), (20,3), (20,7)\}$$

In the experiment design adopted for the considered problem, processing times were randomly generated as uniformly distributed integers, with range (1, 100). As reported by [25], there exist two reasons for generating routing times between 1 and 100. The first is related to the historical evenness. i.e., the majority of research works dealing with the computational tests including scheduling problems, sample processing times from a uniform distribution on (1, 100) or a normal distribution with a mean of 100 and a standard deviation as large as 25. The second reason concerns the fact that it is better to use data that are representative of real scheduling problems. Generating processing times from the uniform distribution of small interval such as (1, 10) for example, are much easier because the dominance rules of [26] create many more ties. As result, optimal solutions become easier to find, which would not necessarily be realistic due to the unsuitable conclusions that may result.

According to several research works that have been done on the test problems for the maximum tardiness criterion, it can be spotted that problem "hardness" depends on two parameters TF and DR [27]. Where the first represent the tardiness factor that affects the average number of jobs tardy, and the second parameter corresponds practically to the dispersion range of due dates that controls their variance, respectively. The aforementioned parameters constitute the range from which the due dates of jobs have to be generated. In this context, while P represents the sum of processing times of all jobs, the due dates of jobs d_k were generated randomly using a uniform distribution on the interval:

$$d_k \in \left[P\left(1 - TF - \frac{DR}{2}\right), P\left(1 - TF + \frac{DR}{2}\right)\right] \tag{22}$$

The values of TF and DR have been set following the different scenarios shown in Table 2, Those scenarios represent the different configuration adopted by [22] to fix TF and DR parameters.

Table 2 Due date range and tardiness factor scenarios

Scenarios	Tardiness factor	Due date range
Scenario 1	0.2	0.6
Scenario 2	0.2	1.2
Scenario 3	0.4	0.6
Scenario 4	0.4	1.2

The release date of jobs r_k is another integer parameter generated from a uniform distribution (0, QP), as pointed out by [28], Q is a factor that determines the range of distribution, it has been set to 0.4, and P is the sum of processing times of all jobs. Further, for every problem size, the weight factor α took three different values of 0.25, 0.5 and 0.75, respectively.

As a result, these choices beget 12 different configuration combinations. Thus, as 6 test problems for each combination were generated, 72 experimental conditions were tested.

The proposed MILP were coded in IBM ILOG AMPL 12.6.0 and then solved using CPLEX 12.6.0 software. The digital works were executed in a computer microprocessor core i3, with 4.0 GB of RAM memory. We imposed 3600 seconds as a time limit, i.e., if the optimal solution had not been found, and verified in that amount of time, the process will be stopped.

3.2 Computational results

The computational results are presented in Table 3, this table summarizes the computational CPU time in seconds used by CPLEX to solve test problems and the total number of nodes generated and explored during the branch and bound procedure.

Table 3 Summary of computational results

n	m	α	TF	DR	CPU time (s)	B & B nodes
10	7	0.25	0.2	0.6	1.78	4284
				1.2	1.88	3723
			0.4	0.6	0.89	4197
				1.2	0.85	1143
		0.5	0.2	0.6	1.09	3860
				1.2	0.67	2794
			0.4	0.6	1.04	1617
				1.2	0.95	1302
		0.75	0.2	0.6	1.94	2374
				1.2	1.93	2119
			0.4	0.6	1.25	1229
				1.2	1.00	1068
10	10	0.25	0.2	0.6	3.56	5784
				1.2	1.72	4604
			0.4	0.6	2. 46	3666
				1.2	2.01	3537
		0.5	0.2	0.6	5.58	8684
				1.2	3.65	4244
			0.4	0.6	2.20	5505
				1.2	1.56	5185
		0.75	0.2	0.6	4.60	5343
				1.2	3.58	4044
			0.4	0.6	3.67	4957
				1.2	2.01	3205

Table 2 (Continuation)

n	m	α	*TF*	*DR*	*CPU Time(s)*	B & B *Nodes*
15	3	0.25	0.2	0.6	15.94	17636
				1.2	13.91	14763
			0.4	0.6	13.03	13417
				1.2	12.84	11639
		0.5	0.2	0.6	16.87	20997
				1.2	12.08	20642
			0.4	0.6	14.98	15364
				1.2	11.88	15014
		0.75	0.2	0.6	15.08	19100
				1.2	13.14	18445
			0.4	0.6	14.03	15885
				1.2	6.05	14167
15	7			1.2	79.25	40577
		0.5	0.2	0.6	125.08	65007
				1.2	98.11	31942
			0.4	0.6	74.08	54228
				1.2	30.11	36061
		0.75	0.2	0.6	95.11	63159
				1.2	83.13	54137
			0.4	0.6	89.18	51775
				1.2	45.09	49062
20	3	0.25	0.2	0.6	150.87	170900
				1.2	101.03	100749
			0.4	0.6	135.73	149889
				1.2	109.76	99500
		0.5	0.2	0.6	268.69	198901
				1.2	198.21	104379
			0.4	0.6	233.67	130612
				1.2	100.85	99794
		0.75	0.2	0.6	210.8	164491
				1.2	199.61	110355
			0.4	0.6	254.03	146881
				1.2	216.00	122471
20	7	0.25	0.2	0.6	399.82	233430
				1.2	345.63	230743
			0.4	0.6	397.29	221390
				1.2	296.36	212214
		0.5	0.2	0.6	419.40	323640
				1.2	401.20	283696
			0.4	0.6	399.70	303735
				1.2	321.56	232126
		0.75	0.2	0.6	419. 94	383687
				1.2	212.36	155537
			0.4	0.6	385.88	218405
				1.2	369.55	205890

The first experiments used test problem containing ten jobs and three machines, At this problem size appointed as small, the proposed MILP is able to find the optimal solution within a time limit and more precisely, within reasonable computation times. Nevertheless, for wide size problem, MILP requires relatively excessive amounts of time and the number of nodes explored rises quickly for some problems.

As can be seen from Table 2, several factors related to the experimental design may clarify the sizable dissimilarity in the problem hardness. The most significant revolve around the tardiness factor TF and the due date range factor DR. By fixing α and DR and focusing on the increase of the value of TF, it can be perceptible that the CPU time and the number of nodes explored become smaller. This is due to the trend of manifold jobs to be attributed untimely due date when the tardiness factor increase, which subsequently generate a considerable number of tardy jobs. On the other side, as the value of DR increases, little time variation occurs in solving problem, and search tree becomes small when α and TF are fixed. This outcome can be explained by the feebleness of the bounds resulting from the feasible schedule. When it comes to a wide number of schedules that must be assessed, the computation times increase.

Furthermore, for problem size with more than 15 jobs, the computation times and the number of nodes are comparatively large, this is due to the data taken into account in the experimental design that is tough to evaluate. For instance, when the weight factor, the tardiness factor, and the due date range factor are 0.25, 0.2 and 0.6, respectively, the computation times and the number of nodes for problem with job size equal to 20 represent 99.55 % and 98.16 % of the CPU time and the number of nodes for problem with job size equal to 10. Wholesale, most of the problems can be solved within a bearable time. As the experiment shows, all the 72 test problems were solved to completion in less than seven minutes of computing times.

4. Conclusion

This paper examined the computational properties of an MILP developed to solve optimally the blocking flow shop scheduling problem with different release dates of jobs, where the objective is to minimize the weighted sum of makespan and maximum tardiness. It highlighted that the aspect of the developed MILP is on a large scale greatly in quality of the computation times and the total number of nodes explored in the branch and bound tree. On top of that, the suggested MILP can optimally solve the problem within a reasonable time for a small size problem, but it involves an immoderate amount of time and search tree becomes wide in larger size problems. Notwithstanding, results are considered tolerable since the proposed formulation requires less than seven minutes of computing times.

Based on the research described in this paper, multiples fruitful research areas involving the considered problem comes to mind. Correspondingly, it will be interesting to develop heuristic algorithms for large-sized problems guaranteeing the resolution in a reasonable calculation time. Besides, the development of a powerful exact method for the BFSP under release dates constraint and with maximum tardiness and makespan criteria is also an interesting issue for study. Finally, it will be useful to prolong the bicriteria approach considered in our study to other complex scheduling environments, in particular into the hybrid flow shop scheduling problems.

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Bi-level programming model and genetic simulated annealing algorithm for inland collection and distribution system optimization under uncertain demand

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A B S T R A C T

With the continuous improvement of users' expectation of transportation quality and the continuous improvement of the transportation system in China, the inland collection system plays an increasingly important role in port development. Based on the demand change, this paper measures the disturbance of the demand change to the inland collection and distribution system from ports and customers, it establishes bi-level programming model for transportation route and transportation mode selection. The upper layer establishes the stochastic opportunity constrained programming model with the minimum cost of collection and distribution, the lower layer builds an optimization model with the goal of maximum customer satisfaction. The genetic simulated annealing algorithm is used to solve the bi-level programming model combined with specific examples and compared with genetic algorithm. The result shows that genetic simulated annealing algorithm can not only obtain the optimal solution, but also improve the speed of global convergence. The genetic simulated annealing algorithm is an effective algorithm to solve the bi-level programming model with multiple targets.

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A R T I C L E   I N F O

Keywords:
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1. Introduction

With the rapid development of world economy and continuous growth of the trade volume, container transport industry in china has also entered the new peak of development. The throughput of container terminals has increased dramatically and the inland container transport network plays an increasingly important role in the container transportation system.

The inland collection and distribution system plays an important role in the development of port and hinterland. Therefore, many scholars at home and abroad have done a lot of researches on it. Zhang (2011), and Zhou X. *et al.* (2017) proposed the current port collection and distribution system problems and analysis, and its development status in-depth discussion [1, 2]. Tang and Tan (2009) discussed some shortcomings and corresponding development countermeasures to hinder it [3]. Based on the theory of sustainable development and related policies, Iannone (2012) proposed the model of inland container transport network planning based on the situation of infrastructure resource construction and the service level of nodes and lines [4]. Combined with the status quo of international railway intermodal transport, Sun (2016) put forward multimodal transport bill of lading and international rail transport waybill docking mode, multimodal transport bill of lading operation mechanism [5]. Du and Evans (2008) proposed logistics network transport management which mainly involves the choices of transport mode, the determination of transport routes, etc. [6]. Chang (2008) studied the optimal transport path selection problem in international multimodal transport networks [7].

On this basis, some experts and scholars combined with freight distribution optimization issues to study the specific operations of the organization in the process of related issues. In the study of maritime and inland transport portfolio problems, Arnone *et al*. (2014) established a linear programming model based on port service frequency and customs time to solve the problem of cargo flow distribution optimization for large sparse networks [8]. Under the combined consideration of various feasible paths and modes of transport, Luo and Grigalunas (2003) constructed a traffic distribution model for port collection and distribution systems [9]. Aiming at the distribution of freight container multimodal transportation problem, Chen and Sun (2015) constructed a freight distribution model based on super-network, and introduced the variational inequality theory, and implemented the improved projection algorithm [10]. To solve the problem of the Dominican inland container transport system, Zehendner and Feillet (2014) built a mixed integer programming model with the minimum transit time [11]. Dong (2007) established a comprehensive optimization model of the port collection and distribution system to solve the single cargo, multi-cargo and multi-transport mode combined transport problem [12]. Aiming at the transportation of goods in the integrated transportation network, Liu *et al*. (2016) constructed an integrated transport network design optimization model considering the construction of financial constraints [13]. Nossack and Pesch (2013), Feng *et al*. (2010), Wang and Yun (2013), and Sterzik and Kopfer (2013) introduced the concept of time benefit and established a model with the goal of minimizing the cost of time [14-17]. For the multi-objective logistics network optimization problem, Pishvaee *et al*. (2010) introduced the time window factor [18]. Huang (2013) and Wu (2014) construct the transportation network decision model of mixed axis mode with the goal of minimizing the cost, and used the heuristic greedy algorithm to solve it, and then used the branch and delimitation method to solve the scheme [19, 20].

All of the above studies are about the optimization of the recent inland collection and distribution system when the demands are certain. The mathematical model is established and solved from the angle of the port and the carrier in most of the researches. Ports provide freight services for many large enterprises. To make itself bigger, stronger and farther, ports have to reduce transportation cost, but also improve the customer satisfaction. Involve this into the decision-making process by measuring, which has a very important influence on the decision result. Considering the change of freight demand, the paper integrates customer satisfaction into decision making and constructs a bi-level programming model of transportation route and mode of transportation. Through the mutual influence between the port and the customer, the optimal solution to improve customer satisfaction can be achieved while reducing the transportation cost.

2. Problem description

The mathematical model studied in this paper is described as follows: Cities can transport export goods to the ports by two ways. One is directly from the city to the port. The other is from the city to the port through the transit station. Different transport nodes lead to different driving distance of the path. There are two alternative modes of transport, namely, railway and highway. Because the modes of transportation are different, the unit price and the speed of the transportation are thus different. In order to reduce the transportation cost and improve the customer satisfaction, choosing the best transportation route and the mode of transportation and making the optimal allocation of goods is necessary. The number of each transport node is shown in Table 1.

According to the problems studied in this paper, the following assumptions are made:

- Operation ability and capacity can meet the freight traffic for a period of time;
- This article only considers one type of goods;
- This article only considers two transportation ways-railway and highway;
- Planning period is one year, and during the period, the cargo demand obeys a certain probability distribution.

Variables and parameters required in this article:

a the number of cities;
b the number of transfer stations;
c the number of ports;
i the serial number of city and transit station;
j the serial number of transit station and port;
m the inland transportation ways, m = 1 indicates the choice of rail transport m = 2 indicates the choice of road transportation;
x_{ij}^m the cargo volume from the transport node i to the transport node j by using the transport mode m;
ε_i represents city i's random cargo needs, the distribution function is $\emptyset_i(\cdot)$;
C_{ij}^m the transportation costs of transporting the unit goods from the transport node i to the transport node j by using the transport mode m;
CI_i the operating costs of the container handling unit of the transfer station i;
CP_j the operating costs of the container handling unit of the port j;
S_{ij} the distance from the transport node i to the transport node j;
V_a the relationship between the average velocity and the maximum velocity;
D_{ij}^m the congestion time from the transport node i to the transport node j by using the transport mode m;
V_{ij}^m the transport speed of the transport mode m from the transport node i to the transport node j;
t_{ij}^m represents that the transport time required from the transport node i to the transport node j by the transport mode m;
T represents that the total time required for goods shipped to the port from the city;
Q^m the amount of container carried by the unit vehicle of the transport mode m;
n_{ij}^m represents that the number of available vehicles from the transport node i to the transport node j by using the transport mode m;
α_i $(0 \leq \alpha_i \leq 1)$ represents that the confidence level of the incident that the freight volume meets the transportation demand generated by the city;
ET represents that the earliest service time was agreed between the customer and the port;
LT represents that the latest service time was agreed between the customer and the port.

Table 1 The serial number of each transport node in the container distribution network

Node	Numbering			Quantity
City	1	2	a	a
Transfer station	a+1	a+2	b	a+b
Port	a+b+1	a+b+2	c	a+b+c

3. Used methods

3.1 Bi-level programming model

(1) Model structure

In the process of distribution of goods, the collecting and distributing cost in the ports mainly consists of transportation costs and operating costs. As a result, they are used to describe the cost of inland collection and distribution system in the upper model. However, the lower model is analyzed from the customer's perspective. It aims to maximize customer satisfaction and introduces the route travel time to describe. When the ports provides the freight service for customers, they make decisions aiming at the least collecting and distributing cost. On the premise of this, the customers make the decision with the shortest route time within the time limit agreed with the port. At the same time, the customer's service time has an impact on the decision of the port. Through the mutual influence of the two, the optimal freight transport scheme is obtained. The optimized model structure is shown in Fig. 1.

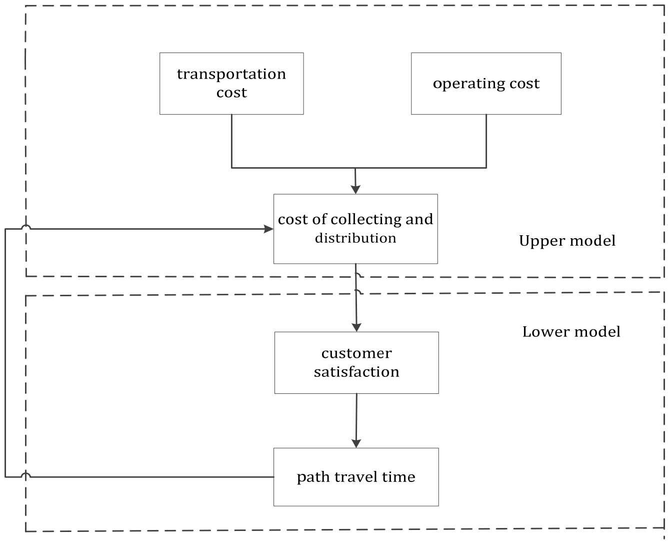

Fig. 1 Model structure

(2) Upper model

The upper model (U) is analyzed from the perspective of the port, taking the minimum cost of the port set as the goal, the target function is set as follows:

$$minf(x) = \sum_{i=1}^{a}\sum_{j=a+1}^{a+b+c}\sum_{m} C_{ij}^{m}\cdot x_{ij}^{m} + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m}\left(C_{ij}^{m} + CI_i\right)\cdot x_{ij}^{m} + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m} CP_j\cdot x_{ij}^{m}$$

Among them, the first item indicates the total cost of transportation to the port and inland container station; the second item represents the sum of the transportation cost from the inland container transfer station to the port and the operating cost of the inland container transfer station to handle the container cargo; the third term indicates the operating costs of the container port for handling all containerized cargo.

Constraint condition:

$$\mathrm{Pr}_i\left\{\sum_{j=a+1}^{a+b+c}\sum_{m} x_{ij}^{m} \geq \varepsilon_i\right\} \geq \alpha_i, i = 1, 2,\cdots, a \tag{1}$$

$$x_{ij}^{m} \leq Q^{m} n_{ij}^{m} \tag{2}$$

$$\sum_{i=1}^{a}\sum_{j=a+1}^{a+b}\sum_{m} x_{ij}^{m} = \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m} x_{ij}^{m} \tag{3}$$

$$\text{When } i = 1, 2,\cdots, a, j = a+1, a+2,\cdots, a+b+c \tag{4}$$

$$\text{When } i = a+1, a+2,\cdots, a+b, j = a+b+1, a+b+2,\cdots, a+b+c \tag{5}$$

Constraint condition (Eq. 1) indicates that the amount of goods transported to the port by the city satisfies the demand for transport demand arising from the city should not be lower than the given confidence level. Constraint condition (Eq. 2) indicates that the operational capacity of the port can meet the volume of goods shipped to the port by the city. Constraint condition (Eq. 3) express the amount of goods transported to the transfer station is equal to the amount of the goods transported to the port by the transfer station. Constraint condition (Eq. 4) express the transfer station or the port is the terminal point when city is the starting point. Constraint condition (Eq. 5) represents that the port is the terminal point when the transfer station is the starting point.

(3) Lower model

The lower model (L) takes the customer satisfaction as the goal, and introduces the path driving time to carry on the characterization. Within the service time agreed between the customer and the port, the shortest route time is the target, and the objective function is set as follows:

$$minT = \sum_{i=1}^{a}\sum_{j=a+1}^{a+b+c}\sum_{m} t_{ij}^{m} + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m} t_{ij}^{m}$$
$$= \sum_{i=1}^{a}\sum_{j=a+1}^{a+b+c}\sum_{m}\left(\frac{S_{ij}}{V_a \cdot V_{ij}^{m}} + D_{ij}^{m}\right) + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m}\left(\frac{S_{ij}}{V_a \cdot V_{ij}^{m}} + D_{ij}^{m}\right)$$

Among them, the first item indicates transportation time from the city to the port and inland container transfer station; the second term indicates the transportation time from the inland container transfer station to the port.

Constraint condition:

$$\Pr\{ET \leq T \leq LT\} \geq 85\ \% \tag{6}$$

$$\text{When } i = 1, 2,\cdots, a, j = a+1, a+2,\cdots, a+b+c \tag{7}$$

$$\text{When } i = a+1, a+2,\cdots, a+b, j = a+b+1, a+b+2,\cdots, a+b+c \tag{8}$$

Constraint condition (Eq. 6) indicates that the travel time of the path is not less than 85 % within the service time range. Constraint condition (Eq. 7) indicates that the transfer station or port is the end point when the city is the starting point. Constraint condition (Eq. 8) means that the port is the terminal point when the transfer station is the starting point and

3.2 Bi-level programming model solving steps

(1) Determine the demand

In the random opportunity constraint condition (Eq. 1), ε_i represents the random demand for city i goods. The confidence level $\alpha_i (0 \leq \alpha_i \leq 1)$ to be achieved for each city i, there is always a number K_i, so that $\Pr_i\{K_i \geq \varepsilon_i\} \geq \alpha_i, i = 1, 2, \cdots, a$ established.

So, the sufficient and necessary conditions for the establishment of constrained condition Eq. 1 is:

$$\sum_{j=a+1}^{a+b+c}\sum_{m} x_{ij}^{m} \geq K_i\,, \quad i = 1,2,\cdots,a.$$

Thus, the key to making the constraint a deterministic constraint is to express the critical value K_i with a known distribution. Known from the knowledge of probability theory, the formula $\Pr_i\{K_i \geq \varepsilon_i\} = \emptyset_i(K_i), i = 1, 2, \cdots, a$ is always established. It can be concluded that $K_i = \emptyset_i^{-1}(\alpha_i), i = 1, 2, \cdots, a$ is always established, where $\emptyset_i^{-1}(\cdot)$ is the inverse of $\emptyset_i(\cdot)$. Since there is more than one solution of the formula $\Pr_i\{K_i \geq \varepsilon_i\} \geq \alpha_i, i = 1, 2, \cdots, a,$ the corresponding $\emptyset_i^{-1}(\alpha_i)$ is not unique. For this situation, the boundary value $K_i = inf\{\emptyset_i^{-1}(\alpha_i)\}, i = 1,2, \cdots, a$ is taken as the solution.

(2) Genetic simulated annealing algorithm

The uncertainty of the bi-level programming model is very high, and the difficulty of solving is very high. Currently, the solution of bi-level programming is mainly embodied in the following aspects: For the linear bi-level programming, Zhao and Gao proposed penalty function method to solve the problem of bi-level programming [21]. Wan, Ji and Wang use a dual approximation algorithm to solve the problem of bi-level programming [22]. For the nonlinear bi-level programming, Sun and Gao proposed a heuristic algorithm based on sensitivity analysis [23].

In recent years, some intelligent algorithms are widely used to solve the problem of transportation bi-level planning model, such as genetic algorithm and cloud adaptive genetic algorithm, etc. Although the genetic algorithm can solve the model directly under the uncertain rules through a global search of feasible solutions, but its search speed is slow, easily to fall into the local optimal solution and do not converge. Obviously, the transport routes and transport modes for the uncertainty cannot be accurately described.

The simulated annealing algorithm (SA) has high quality and robust initial experimental performance. Some scholars have studied the probability of using the simulated annealing algorithm to solve the global minimum point, and found that the obtained probability value is very close to 1. Therefore, the simulated annealing algorithm will not fall into the local optimal solution until it finds the global minimum point, but this optimization process is often longer. Combining genetic algorithm with simulated annealing algorithm to obtain a hybrid optimization algorithm-genetic simulated annealing algorithm (GASA), which makes the two algorithms make up for each other and the defects are well compensated. Therefore, this paper uses genetic simulated annealing algorithm to solve the transport routes and transport modes selection of bi-level programming model.

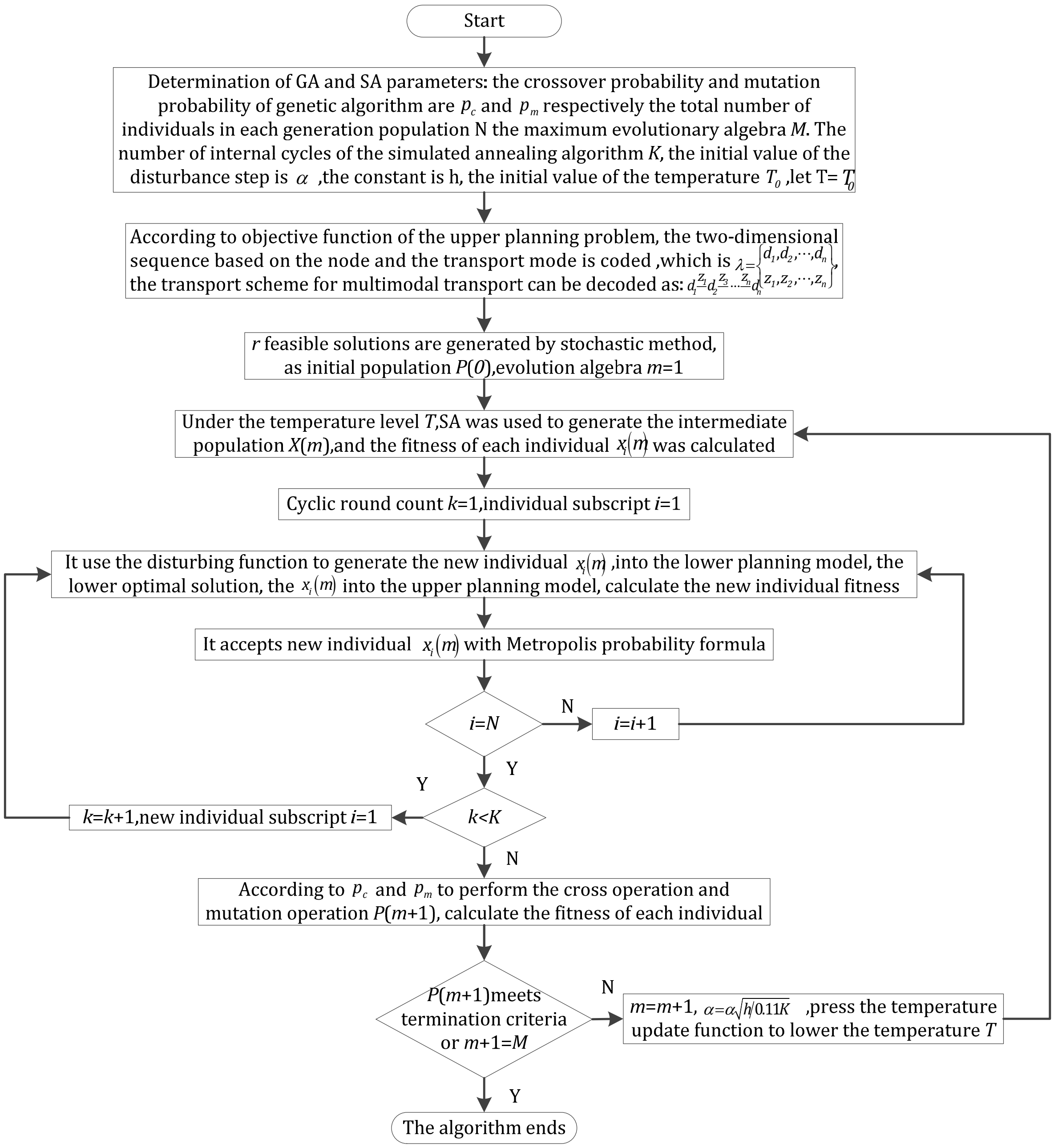

Fig. 2 Algorithm flow chart

First, according to the decision-making scheme of the inland container transit station obtained from the upper model, the transportation route and transportation mode of the lower model are selected and optimized; secondly, the upper cargo transportation plan is adjusted through the optimization of transportation methods and routes. Followed by the optimization of the transport routes and transport methods back to the upper model to re-distribution of goods; finally it is expected to converge to the near-optimal solution of bi-level programming through several iterations, the algorithm flow is shown in Fig. 2.

4. Results and discussion

4.1 Data sources

The example selects one hinterland city, three locations where inland container transit stations can be built and two ports form an inland collection and distribution network. The optimization problem of transportation demand satisfying the confidence level of 90 % was studied, the relevant data is shown in Tables 2-14. Due to different modes of transport, there are differences in capacity limits. The means of transport for railway transport are container regular trains, the unit load is 140 TEU, road transport is a container truck with a unit carrying capacity of 2 TEU.

Table 2 The number of cars available from city to port

Node	Port 1	Port 2
City	13205	52823

Table 3 The number of cars available from city to transit station

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	1758	4746	8575

Table 4 The number of cars available from transit station to port

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	8167	11398	24374
Port 2	15818	38954	85275

Table 5 The number of trains available from transit station to port

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	122	156	261
Port 2	100	100	200

Table 6 The number of trains available from city to transit station

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	100	50	0

Table 7 The unit freight rates of road from city to port (Yuan/TEU)

Node	Port 1	Port 2
City	4242	2126

Table 8 The unit freight rates of road from the city to the transit station (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	834	3968	5092

Table 9 The unit freight rates of road from the transit station to the port (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	1063	1913	2563
Port 2	1175	2192	2750

Table 10 The unit freight rates of railway from the transit station to the port (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	965	1436	1871
Port 2	1190	1687	2122

Table 11 The unit freight rates of railway from the city to the transit station (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	1398	2714	0

Table 12 The distance between city and port (Km)

Node	City
Transfer station 1	425
Transfer station 2	405
Transfer station 3	356
Port 1	1100
Port 2	945

Table 13 The distance between transit station and port (Km)

Node	Port 1	Port 2
Transfer station 1	424	445
Transfer station 2	556	356
Transfer station 3	439	357

Table 14 Transfer station and port operating capacity and unit service fee

Node	Operational capability (TEU / year)	Unit service charge (Yuan / TEU)
Transfer station 1	140000	220
Transfer station 2	100000	240
Transfer station 3	140000	200
Port 1	500000	350
Port 2	140000	340

4.2 Demand calculation

Through investigation and statistics of the city's 52-week demand for transportation within a year, it is found that transport demand is not uniform, as shown in Fig. 3.

(1) Mathematical expectation. Using Eviews software to analyze the above-mentioned 52-week transportation demand, the demand for transportation within one year obeys the normal distribution. The expected value is 2034 and the standard deviation is 110. Since random variables are additive, the transport demand for this year follows a normal distribution, which is $\varepsilon_i \sim N(105768, 735^2)$. The expected value is 105768 TEU and the standard deviation is 735 TEU.

(2) Maximum shipping value. Assuming that the port needs to meet 90 % of the city's transportation, which means $\alpha_i = 0.9$. According to the standard normal distribution table, there is $\emptyset(1.28) = 0.9$. So, the maximum freight (K) obtained to meet the stochastic demand with 90 % confidence level is $K_1 = \varepsilon_1 = min\{105768 + 735 \times 1.28, 105768 + 735 \times 1.29\} = 106709(\text{TEU})$.

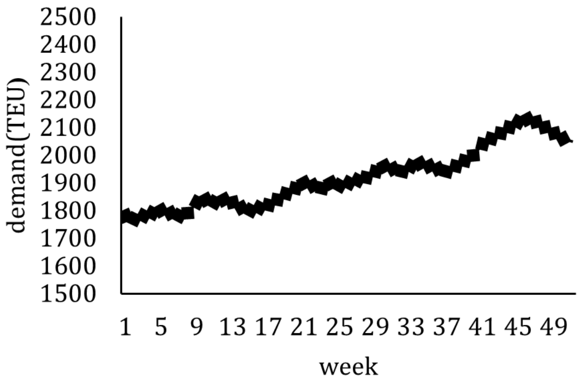

Fig. 3 The demand for container transportation generated every week within a year (Unit: TEU)

4.3 Numerical result

According to the example, we can see that a = 1, b = 3, c = 2. Number 1 stands for the city, and number 2-4 is three container terminals, and number 5, 6 is respectively for the two ports. The population size of genetic algorithm N = 100 and the number of evolutionary M = 100; the number of internal cycles in simulated annealing K is 20 and the constant h is 50; the initial value of step α is 0.1 and the initial temperature T_0 is 2000. Temperature reduction scheme: For the first 20 generations, T is subtracted by 20 % of the current value, after each generation T minus 50 % of the current value. The weight vector of cost of collecting and dispatching and path travel time is ω= (0.4, 0.6). Suppose the railway transport speed is 80km/h, the highway transportation speed is 100km/h, and the service time agreed by the customer is [9, 11]. Genetic simulated annealing algorithm is used to solve the problem of inland collecting and dispatching system optimization under the change of freight demand, the result is shown in Table 15.

Genetic simulated annealing algorithm and genetic algorithm were used to solve the optimization problem of inland collection and distribution system, the results are shown in Table 16-17 and Figs. 4-5. According to the calculation results, the optimal value of the model calculated by genetic simulated annealing algorithm is better than that of the traditional genetic algorithm in the same evolutionary algebra. The success rate of the search is higher than that of the genetic algorithm, the ability of the algorithm to search the global optimal solution is optimized. The convergence precision and the robustness are improved, and the global convergence speed is improved effectively. It can be seen that the genetic simulated annealing algorithm can effectively and quickly solve the bi-level programming model. It can improve customer satisfaction and reduce the cost of collection and distribution by choosing the rationalization of transport modes and transport routes in the process of making the cargo flow distribution plan.

Table 15 Calculation results of genetic simulation annealing algorithm

Project	Minimum value	Maximum value	Optimum solution
Time/d	9.00	12.00	9.55
Cost / million	245910.61	418469.45	248120.96

Table 16 Calculation results of genetic algorithm

Project	Minimum value	Maximum value	Optimum solution
Time/d	9.45	11.00	10.61
Cost / million	248378.12	414468.33	255020.98

Table 17 Comparison of Genetic simulation annealing algorithm and genetic algorithm

Method type	Best transport plan	Optimization degree, %
GASA	$1\overset{2}{—}2\overset{1}{—}5,1\overset{2}{—}6$	58.2
GA	$1\overset{1}{—}2\overset{1}{—}5,1\overset{2}{—}6$	46.3

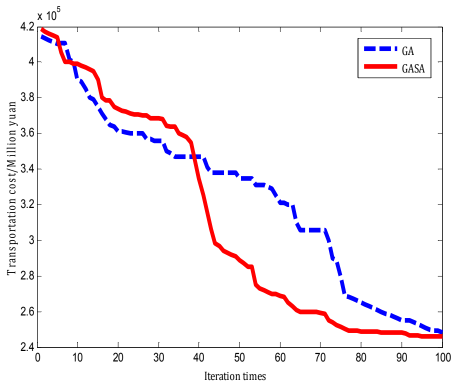

Fig. 4 Transport cost comparison chart

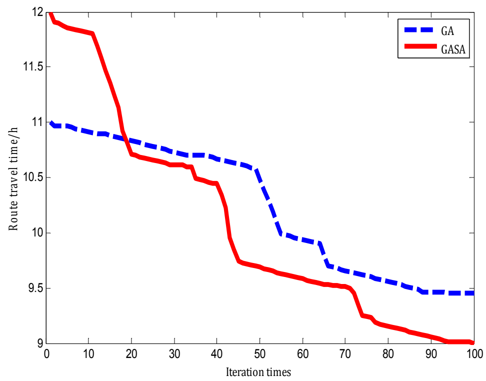

Fig. 5 Route travel time comparison chart

5. Conclusion

Considering the uncertainty of freight demand, the bi-level programming model for the selection of transportation routes and transportation modes was established from the perspective of lowering transportation costs and improving customer satisfaction. The genetic simulated annealing algorithm is used to solve the model and the optimal scheme is obtained. Finally, the validity and feasibility of the model and algorithm are verified by simulation experiments. On the container inland collection and distribution system optimization problem, the combination of the bi-level programming model and the genetic simulated annealing algorithm provides a balanced language model and solution for the port. It has certain practical value for improving customer satisfaction and reducing the cost of collecting and transporting.

The optimization of inland collection and distribution system is a very complicated problem. In terms of transportation, this article only considers the two ways of railways and highways. In the study of specific issues, the transportation of inland river should also be considered in light of actual conditions.

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In-process non-destructive ultrasonic testing application during wire plus arc additive manufacturing

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A B S T R A C T

Additive manufacturing is a technique which builds structures by depositing material in a layer-by-layer manner. Wire plus arc additive manufacturing technology also belongs into this group of manufacturing processes. It has been investigated in the last twenty-five years, although the first patent dates from 1925. Wire plus arc additive manufacturing uses existing welding equipment, an electric arc as the heat source, and wire as the feedstock. In this paper, we explain some basic process planning and implementation techniques, as well as the main advantages and disadvantages of the process. In addition, we discuss the potential of in-process non-destructive ultrasonic testing application to this process, in order to inspect the quality of the part while it is being produced, and to enable eventual repairs in-situ. Some authors have already presented the idea of non-destructive testing for AM products, and stated that ultrasonic testing could provide the most reliable results for detecting the lack of fusion, porosity, and other possible flaws. While researches so far were limited to post-process testing, this paper proposes the idea of in-process testing, which could provide a chance to find the flaws and the defects earlier in order to change the parameters in-situ, and avoid production of the whole part if it is already recognised as unacceptable. Despite some constraints, we believe the proposed method has great potential and represents a challenge worth investigating in more detail in the future.

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A R T I C L E I N F O

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1. Introduction

Thanks to the development of modern industries, there is always a continuous need for investigating and developing new technologies. One of the examples is the Aerospace industry, which will need about 20 million tonnes of raw material in the next 20 years [1]. Due to high safety standards, and considering the fact that this industry requires distinctive materials like titanium and other special alloys, which are expensive to produce and often not so suitable for machining [2], it is clear that production solutions need to assure minimum failures. Additive Manufacturing (AM) technologies are applied increasingly. A basic AM system consists of a combination of a motion system, heat source and feedstock. Unfortunately, most of the conventional AM technologies use only polymer materials or metal in powder form, resulting usually in porous structures [3], which is often not good enough to make fully functional products [4]. On the other hand, Wire plus Arc Additive Manufacturing (WAAM) offers a solution to solve the structural functionality issues related to most other AM technologies.

WAAM has been investigated in the last 25 years, despite the fact that the first patent dates from almost 100 years ago, from 1925 [5]. The heat source used in WAAM is electric arc, and the additional material is welding wire, which makes it a combination of welding and AM technology. In addition, WAAM uses ordinary welding equipment (power source, torch, shielding gases, etc.), but combines it with robotic systems or CNC machines, which move the torch and wire feeder. It should surpass present technologies for producing fully functional metal products (especially aerospace components), which can be very big in size. A high deposition rate (usually 50-130 g/min, depends on method), low cost and safer operation makes it desirable [6]. However, there are still challenges to be resolved, like the residual stresses and deformations due to enormous heat input, relatively low part accuracy and rough surface (post-processing is needed) [7]. Some of these problems have already been reduced. Yet, there are still some challenges that need to be investigated further. In this paper, we present a possibility to apply in-process Non-Destructive Testing (NDT) within the WAAM in order to inspect the quality of the part while it is being produced, and to enable eventual repairs in-situ.

2. WAAM process planning and implementation

Firstly, just like in any other AM technology, a 3D CAD model of desired part has to be made. These models can be designed in appropriate software or using reverse engineering (3D scanning). The designed part is then saved in standard convenient format, usually ".stl" (Standard Tessellation Language), and it serves as a link between the software (CAD model) and machine for processing, providing the basis for slicing part into layers [6]. Software „slices" the part on more layers per height and a layer's 2D contour is used for generating a tool (torch) path. For the parts which have the same cross-section per entire height, the first contour is the same as the last one, and as every one between them. Problems usually appear for the parts where the cross-section is changing with height; the process is more complex and difficult, due to the need for generating more tool paths. The next step in the process is choosing suitable welding parameters (wire-feed speed, welding speed, amperage and voltage of welding current, etc.) and bead modelling. Using the generated tool path and chosen welding parameters, the product is then made in layer-upon-layer fashion (the first layer is deposited on the base plate, the torch goes up and deposits the second layer onto it, and the process continues until the whole part is made). Additionally, a post-process machining path can be generated, or post-processing can be done independently [8]. Heat treatment is also usually done after the process itself. The schematic diagram of the complete WAAM based process is shown in Fig. 1 (on the left) [8, 9], and an example of a WAAM system with its main features is shown in the same Figure on the right-hand side.

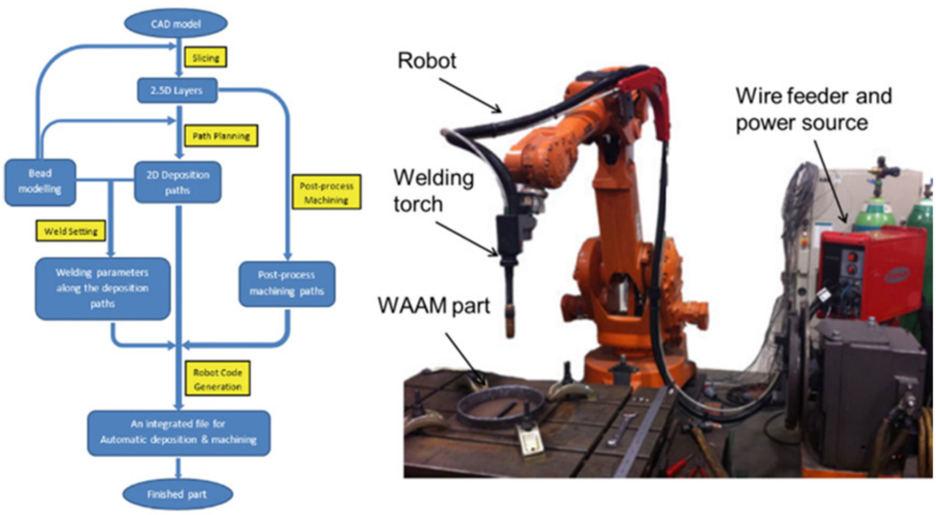

Fig. 1 Scheme of WAAM process (left) and example of WAAM system (right) [8, 9]

Even if the process seems to be quite easy and simple, it must be clear that all of the main steps contain smaller and numerous sub-steps, which have to be calculated and implemented carefully in order to get the part as good as possible. Slicing algorithms have been developed to provide layers of better quality [10]. Different path patterns [11] or bead modelling methods [12] were investigated for the same reason. Also, there has been a lot of research conducted regarding optimisation of welding parameters [13, 14]. All these investigations led to a conclusion – this is a complex process, and every mistake in any of the steps can cause major mistakes, affecting the part's surface finish, microstructure, mechanical properties and overall quality. If everything is done correctly, parts can be made like the one shown in Fig. 2 [6].

MIG (Metal Inert Gas) is the welding method, which is mostly used in WAAM technology. The wire is coaxial with the welding torch, which leads to an easily generated tool path. CMT (Cold Metal Transfer), a special metal transfer process in MIG welding, is used often. Using CMT means it is necessary to control welding parameters more strictly, but it can provide excellent quality of the layers, with lower heat input and almost without spatter. It is convenient for materials like steel and aluminium, but when it comes to titanium, this process is affected by arc wandering, so it produces a very rough surface. Due to that, TIG (Tungsten Inert Gas) welding is used more often for producing titanium parts. These processes need external wire feeding, and to obtain a product of good quality, the wire has to be delivered always from the same direction. It means additional torch rotation is necessary, which complicates robot programming and tool path generation [5].

Fig. 2 Producing WAAM part (left) and partially post-processed part (right) [6]

3. Advantages and disadvantages of WAAM

WAAM advantages are numerous. Investment and material costs are low because there is no need for buying special machines or systems. If a robotic hand or CNC machine are already available, they just need to be combined with the welding system, and material can be bought as welding wire. The choice of materials is wide. Deposition rates are much higher compared to other AM technologies (depends on the method, but goes up to 130 g/min, and it can reach even 10 kg/h, but then it compromises part accuracy). There is less waste, and that is important, especially in the Aerospace industry, where the cost is evaluated by the Buy-To-Fly (BTF) ratio, which is the ratio of the initial work piece mass to the finished component mass (it can be expressed in volume). Using WAAM, it can be reduced below 2, while, when using traditional manufacturing methods, it can go up to 20. This means it is possible to make a part which weighs 10 kg by buying 20 kg of raw material (feedstock) using WAAM, and for traditional methods 200 kg of raw material could be necessary for the same part. For some materials, this means huge cost savings. WAAM also enables short lead-time production and near-net-shape processing, which makes the whole manufacturing process faster and shorter. Additionally, part size is almost unlimited (it is limited only by the possible base plate size, or by the size of the chamber used to create the protective gas atmosphere, if it is needed) [5, 15].

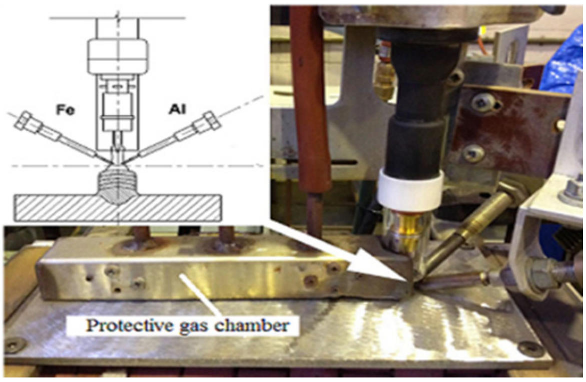

Fig. 3 Producing Fe_3Al using WAAM technology [16]

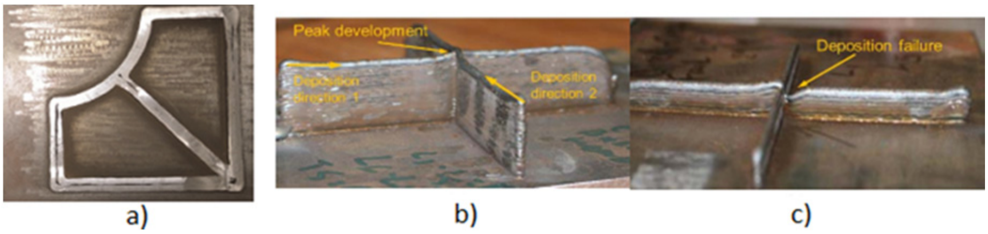

Fig. 4 Cavities (a), excessive camber (b) and sag (c) [1, 11]

It can offer a solution for producing functionally graded materials – they are characterised by the change in their composition and structure progressively over volume, which results in corresponding modifications in the properties of the material. Materials like these are usually produced for particular applications due to their specific properties, and one of the most used is iron aluminide, Fe_3Al. The process of producing that kind of material is shown in Fig. 3 [16]. Also, some researches showed that particular mechanical properties of WAAM material match, or even exceed, properties for the same cast or wrought material. Strength and ductility can reach these properties [17], and fatigue resistance can be even better [18]. All of these advantages are already well-known, and they make WAAM a desirable replacement for traditional manufacturing methods.

Unfortunately, there are still some disadvantages and constraints which cause problems, and there have been many conducted researches to reduce or avoid these problems.

Firstly, WAAM is more suitable to make large and less complex parts, rather than smaller parts with complex geometry, and this is a constraint which clearly defines its application. [5] Many researchers concluded that the parts produced by using WAAM have anisotropic properties, with higher strength and lower ductility in a horizontal (deposition) direction [18, 19]. Some issues related to bead modelling can also occur. Bead modelling controls the path planning variables, and it is used to define optimum welding parameters which can produce appropriate bead geometry. To manufacture parts with good surface quality, low roughness and geometrical precision, it is inevitable to develop both carefully and precisely – single weld bead geometry and multi-bead overlapping model [12]. If it is not done correctly, issues like excessive bead overlapping, or vice-versa, insufficient bonding, can occur. Some papers offered a solution to this problem, like the mathematical model TOM (Tangent Overlapping Model), which provides the necessary overlapping for obtaining desirable accuracy and quality [12, 20]. A generating tool path is inclined to defects like porosity, cavities, excessive camber (peak development) and sag (deposition failure). Porosity and cavities can occur in thick parts, which have to be filled inside (Fig. 4a), while camber and sag usually occur in crossing features (Figs. 4b and c) [1, 11].

Issues with porosity and cavities usually occur using the traditional contour pattern, which fills 2D geometry from external boundaries towards the inside. If step-over distance "d" (it is the distance between the two parallel tool-paths for depositing two adjacent layers) is not calculated properly (as the function of weld bead width "w"), then the torch may not melt enough wire and adjacent layers will not bond to each other, leaving cavities inside. The solution for this problem is an innovative technique of using the Medial Axis Transformation (MAT) of the geometry, where the torch starts from the inside and works towards the outside. Using this strategy, it is possible to fill the internal area of the geometry completely, and it has been investigated and explained in detail in some other papers, including [11, 12]. The peak at the layers' intersection appears when the weld beads are overlapping, while deposition failure occurs when too much heat is lost through the base plate and there is a lack of deposited material (accumulated) on one side of the crossing. Instead of depositing cross-like features, layers can be deposited as two „L" shapes which are touching each other at an intersection. This approach was investigated in [1].

Other types of problems that can occur are residual stresses, distortions and deformations, which are typical welding issues. Fig. 5 shows examples of these problems and a possible solution.

Usually, the part is made on one side of the base plate. Due to great heat input, deformation tends to „pull" the base plate in the building direction. The base plate bends, which may also bend the deposited wall and deform it (Fig. 5, a). The base plate can be clamped trying to reduce this, but Fig. 5 (b) shows software simulation for that situation. Residual stresses are released after unclamping the base plate, and no significant progress is made. However, Fig. 5 (c) offers a solution, called symmetrical building, or balanced building strategy [5, 15]. It is required to find the most appropriate plane of symmetry for the component, and the base plate should be set to coincide with that plane. Layers are then deposited on both sides of the plate, and stresses produced on one side are balanced with those produced on the other side. Sometimes two parts are needed anyway, so this is an additional benefit, but sometimes redesign is necessary.

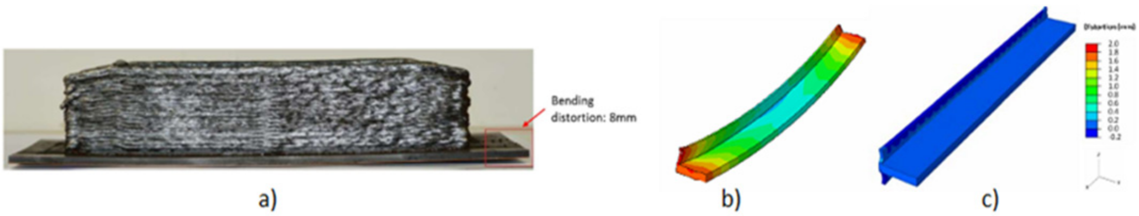

Fig. 5 Deformations (a, b) and solution through balanced building strategy (c) [5, 15]

4. Future trends

Researches on WAAM are interdisciplinary, and there is still plenty of space for improving and introducing new ideas. Some researchers suggest non-destructive testing of produced parts to be included in the process [5]. We elaborate on this idea more thoroughly in the next section. Issues with anisotropic properties can be solved using interpass rolling, which is also a subject of investigations [21]. It is even possible to integrate machining simultaneously with the layer deposition process, which would reduce the need for post-processing [22]. Some researches introduce new materials (besides steel, titanium and aluminium), like magnesium, to this process [23]. Also, there is a chance for complete process automatization, where human interaction would virtually be necessary only to start the process [8]. Further investigations should include work on these ideas and researches, alongside improvement of parameters' optimization, part design, heat treatment, monitoring and process control, which will, altogether, lead to better understanding and implementation of WAAM technology.

5. In-process non-destructive testing

The idea about Non-Destructive testing (NDT) that would be included in the process seems very interesting, but it has to be elaborated in detail. NDT is the common name for an extensive group of testing methodologies and techniques used in engineering, science and industry to assess the properties of a product, part or assembly without destroying it. NDT does not bend, break or affect the part being tested in any way. It is a highly valuable technique that can provide great savings during product and prototypes' design, inspection and testing, or troubleshooting and research. Methods that are used mostly are: Visual testing, liquid penetrant testing, magnetic particle testing, ultrasonic testing, radiographic testing, acoustic emission testing, along with some other, less conventional methods such as, for example, impedance-based monitoring [24]. Each of these methods have their own characteristics, advantages and constraints. Liquid penetrant and magnetic particle testing are cheaper and easier to carry out, but can only show defects on a part's surface and a few millimeters below. Ultrasonic and radiographic testing are more expensive and require more time for training, but can show defects in the entire part [25]. Considering problems, needs, requirements and defects which can occur in WAAM produced parts, ultrasonic testing seems to be the most appropriate method to improve the development of this process and the part being produced in this manner.

Ultrasonic testing (UT) is based on the same principle as, for example, ultrasound fish finders on boats, or ultrasound examination of the foetus during pregnancy. Ultra-high frequency sound is released inside the tested material, and if the beam strikes a material with a different acoustic impedance (density and acoustic velocity), part of the beam returns back to the probe and can be shown on the display of a UT machine. Material with a different acoustic impedance is usually some flaw in the part which is being inspected (gas particle, cavity, porosion, etc.). the position and size of the defect can be determined by knowing the speed of sound in the part and amplitude of the sound source. An ultrasonic transducer (probe) is used to introduce the sound into the part. It converts electrical impulses from the UT machine into sound waves. When these waves reflect back, it converts them back so they can be presented as sf visual signals on the display. If the machine is tuned and balanced (a special process called calibration), a qualified Inspector can calculate the distance from the probe to the indication. If the Inspector is experienced, he should also be able to define the type of defect (inclusion, cavities, slag, porosity or cracks in a material) that caused the indication. Ultrasound cannot travel through air, and use of a couplant is necessary. The couplant could be some liquid (water, oil) or a gel. It is used to transmit ultrasound from the probe to the material, and it is put on the surface of the tested part. The most common sound frequencies used in UT are between 1 and 10 MHz, which are too high for human ears to hear. The lower frequencies have greater penetrating power, and can detect the flaws at greater depths, but their sensitivity (the ability to detect small indications) is lesser, while the higher frequencies do not reach greater depths, but can detect smaller indications. The two types of sound waves which are used mostly in common inspections are the compression (longitudinal) wave and the shear (transverse) wave. Longitudinal waves are used in straight-beam probes, and shear waves are used in angle-beam probes.

The basic principle of UT can be seen in Fig 6, where an initial pulse (sound introduced to a part) and back surface echo (sound reflected from the back wall of the part) can be seen. They are always seen on the screen of the UT device. Everything else that appears between these two signals is some indication. Of course, it is not so easy to carry out these inspections, and that is why UT requires a well-trained and skilful operator, who can distinguish false signals from real flaws in the material.

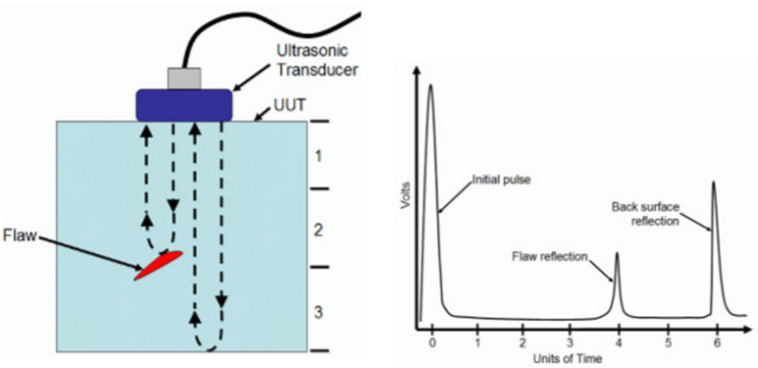

Fig. 6 Ultrasonic testing principle [26]

An important part of UT is preparation for inspection, which includes calibration of the equipment. A UT system is very sensitive, and calibration has to be carried out before each inspection. Sound speeds are different in different materials, and those speeds affect the accuracy and precision of the obtained results. Probes have to be calibrated on the same material as that which will be inspected. Etalons used for calibration are standardised, their composition and dimensions are known, and so probes can be adjusted correctly. Some of the advantages are: Depth of penetration and reach for defect detection or measurement easily surpasses possibilities of other methods; it is usually enough for an operator to test only one side of the product; it can characterise defects in detail, giving information about size and distance from the probe; etc. Main disadvantages are: Surface must be accessible to the probe and couplant, as clean and flat as is possible; operators have to be very skilful and well-trained (more effort is necessary than for other NDT methods); thin parts may be difficult to inspect; etc. [27].

The question is how UT can be combined with WAAM technology, and what benefits can it bring? First of all, it is important to mention that, to the authors' best knowledge, no one has ever tried to integrate UT directly in the WAAM process. Some authors, like [5], just mentioned the idea of it like a suggestion for future researches. So far, the only contribution to UT application in WAAM is reported in [28], where the authors tried to evaluate the results of three different NDT methods used to inspect WAAM products. The biggest difference between their approach compared to our idea is the place of UT in the whole process – they tested WAAM parts once after they had been made. It is almost like ordinary ultrasonic testing, because when a part is finished, it can be treated just like any other part made using any conventional method. There are also numerous papers regarding NDT of AM parts, but with regards to online process monitoring, all of those papers are irrelevant, because they did not make any contribution to the theory that UT can be included directly in the process. However, on the other hand, paper [28] confirmed the fact about the biggest problem for application of UT in WAAM technology – an irregular surface. UT probes are very sensitive and they require as flat a surface as possible. It could be hard to achieve implementation of UT during the deposition process, but some ideas, which include machining during the process (Fig. 7), are introduced in [22], and they can make further innovations possible.

In [22], the researchers introduced a new idea for WAAM technology, adding a new tool for the CNC machine which moves the welding torch, and they managed to achieve in-process milling, which makes the surface finer and more appropriate for UT. That would fulfil the first requirement for inspection. In addition, another "tool" designed just to hold the probe, which will go after the surface milling tool and look for flaws in the produced layers (Fig. 8a), should be added to the same CNC machine. The probe does not have to follow the milling tool after every pass, but it can go after a particular number of deposition passes, for example. The simple straight-beam probe will be good enough to provide the necessary results. If the part is not thick or high enough (there was not a sufficient number of passes), then a double straight beam-probe can be used. Its principle is the same as of the ordinary straight-beam probe, but it can detect flaws which are closer to the surface. Some solutions could also include two probes (one would be a transmitter of the signal, and the other one would be a receiver). This solution has to be combined with side milling, and probes would not slide across the part's surface, but across two lateral sides (Fig. 8b). The tool holder should be designed differently than in the first two cases, but the results should be the same. Some manufacturers also produce special probes for a particular application, which may reduce the need for milling (special probes could overcome the problems regarding surface roughness), but they are much more expensive than ordinary probes, so they should be used only if machining is not possible for some reason.

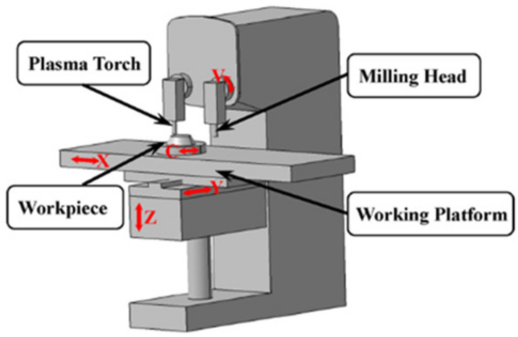

Fig. 7 CNC machine with welding torch and additional tool for milling [22]

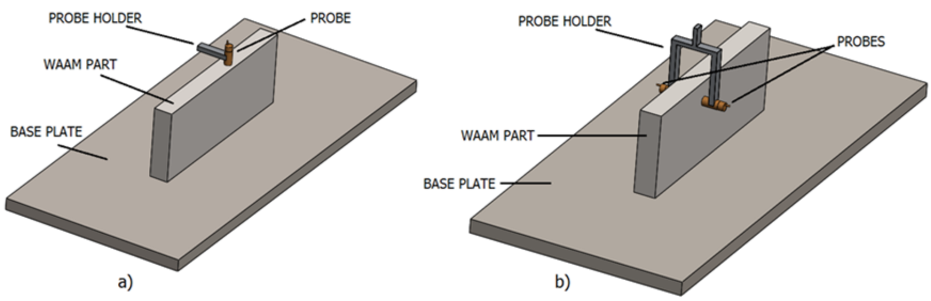

Fig. 8 Simplified preview of possible solutions for ultrasonic testing of WAAM parts

Another possible solution could be the idea proposed in [28], where the UT probe is applied from the bottom of the base plate, which is shown in Fig. 9. A problem that can occur with this method is when the materials of the base plate and wire are not the same, which is not rare in WAAM processes. In that case, signals appearing on the boundary of the two materials have to be taken into consideration.

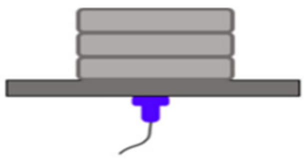

Fig. 9 Ultrasonic testing with probe on the bottom of the base plate

Regarding all of these ideas, what benefits for WAAM are possible by applying in-process UT?

- *Online monitoring*. By applying in-process UT there would be no more need to wait until the whole part is finished before inspection, as the proposed method provides the possibility to inspect the part while it is being produced, which means that most of the defects can be seen virtually at the moment when they appear.
- *Repairs in situ*. The proposed in-process testing application enables the operator to stop the process due to the appearance of defects, and resolve the problem immediately.
- *Detection of numerous flaws at a whole cross-section of a part* – UT enables detection of different kinds of defects (porosities, cavity, unwanted gas or solid particles) in the WAAM part. As UT is a Non-Destructive Testing method, the part remains undamaged, and can be used after inspection.
- *Detection of microstructural changes*. UT does not only find the flaws, but it can even indicate microstructural changes that can cause anisotropic mechanical properties. When the grains are bigger and coarser, there will be more attenuation (the ultrasound will lose more power going through the material). That will be seen on the screen as weaker signals, which is a sign for an operator to adjust some manufacturing parameters.

- *Money and material savings*. Probably the most important advantage of this approach. Using UT after the part is made usually means the whole part has to be thrown away if defects could not be repaired. However, if defects could be seen during the process, the process could be stopped at the moment the defects occurred, and that could save further material wasting. After detailed testing (if it is needed), additional work should be done to remove the defect if it is possible, and to ensure it does not occur anymore.

Of course, the idea proposed in this paper also has some constraints which need to be taken into account before real-life application.

- *Longer and slower process*. Probes should not be exposed to high temperature differences from the etalon to the material in order to work properly. The part temperature should not differ too much from the temperature of the etalon used for probe calibration. This means the part has to be allowed to cool for a while after deposition, which would make the entire process slower and longer.
- *Machining is necessary*. The only solution to avoid machining (at least some part) is to look for specially designed probes. They are more expensive, more difficult to be designed and produced, and cannot always guarantee correct results if they are not used on the part which they are intended for. Ordinary probes are a better solution, but, in this case, machining is inevitable.
- *A new tool path has to be generated*. A new tool path for the UT probe has to be generated just like for the additional machining.
- *Anew tool holder is necessary*. Another requirement is anew tool holder. Generally, it should not be a problem to make it, due to its simplicity. It would only require a modern CNC machine or robotic hand which is capable of holding and exchanging more tools.
- *More expensive process*. Ultrasonic testing is not cheap. Operators have to be well educated and trained, and modern equipment is expensive, which makes paying for the service or developing own human and equipment resources very demanding.

Despite all the constraints just mentioned, we believe the application of UT in the WAAM process has a great potential, and represents a challenge worth investigating in more detail in the future. All potential problems and constraints can be solved, while the benefits of the proposed in-process UT application are certainly interesting enough to put more effort into its realisation. This is one-step forward in entire WAAM process automation, despite the fact that it is still not totally possible. No matter how modern equipment is, human interaction in calibrating and monitoring the inspection process is still necessary.

6. Conclusion

WAAM technology is the future for researching and commercial use, regarding all of its advantages and disadvantages. Good process speed, wide choice of materials, the acceptable price of equipment and feedstock, along with good mechanical properties, are some of the reasons why some specialists predict that WAAM technology will be more and more present in some industries, especially in the Aerospace industry. Although it is not suitable for making parts with complex geometry, the possibility of making large metal parts is more important. Conventional AM technologies use mostly polymers, and even if there have been more polymer parts in recent years, which are fully functional products, for some industries metal parts are still required. In addition, there is no need for some special equipment, as only some knowledge about how to connect computer software to existing welding systems is necessary. Disadvantages like porosity, cavities, residual stresses and deformations have already been avoided with some methods, or at least there is a way to reduce their influence. Post-processing still remains a disadvantage, and for now it has to be accepted as a necessary setback, but other technologies have things like that as well. This technology is a combination of welding (which is one of the most popular and most widespread technologies) and additive manufacturing (which is already present, but it is also the future), and it is clear why it is so interesting in research and also from a commercial perspective. It is already developed enough for everyday use in some industries, but there is also a lot of space for future researches, improvements and experiments, which will help to reduce and avoid existing problems and to use the advantages of this technology even more. We believe one of the most interesting new possibilities could be in-process ultrasonic NDT application. Since there already are detailed researches on how UT can be applied on finished WAAM products, and how it is possible to integrate processes like machining during the WAAM process, including of online UT during WAAM is a novel idea which has firm grounds. Of course, future work should base on experimental setups that should prove this is tenable suggestion, and that could be a topic for further researches and papers. There are some problems and constraints that needs to be resolved, but the benefits of the proposed method are very challenging. Even though it is still not possible to achieve total process automation, this is certainly a step forward, a contribution to ideas for WAAM process development and an interesting basis for future work.

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A robust hybrid heuristic algorithm to solve multi-plant milk-run pickup problem with uncertain demand in automobile parts industry

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A B S T R A C T

Considering the actual situation of China's automobile industry, this paper pioneers the discussion of the multi-factory milk run pickup problem with uncertain demand and frequency (MFMRPP-UDF). Considering the balance between inventory cost and distribution cost, a mixed-integer programming model was built for the problem, and converted into a robust optimization model by the Chernoff-Hoeffding theorem; then, the adaptive genetic algorithm (AGA) and local search (LS) were combined into a general hybrid heuristic algorithm (AGA-LS) to solve the problem. Then, the proposed algorithm was run 10 times and contrasted with the standard GA. The results show that the AGA-LS outperformed the standard GA in the reduction of the overall cost. This research provides important insights into the cost efficiency of inventory and delivery in the automobile parts industry.

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A R T I C L E   I N F O

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1. Introduction

The advent of the Internet has enabled customers to place orders and specialize requirements online. With the increasingly individualized demand, automobile enterprises are competing to implement small-batch and multi-frequency customized production [1]. The ensuing changes of the later stages of the supply chain throw down major challenges to production and logistics, creating the need for lean manufacturing, just-in-time (JIT) production, and production-centred logistics [2-5]. Facing the constantly changing customer demand, automobile enterprises should also maintain the supply of parts at a suitable level to lower the inventory cost. All of these developments call for a good logistic strategy customized production with uncertain demand that can balance inventory cost and distribution cost.

One of the viable strategies is the milk run logistics system. Being a mature and popular distribution strategy [6], the milk run logistics system enables suppliers located close to each other to transport goods to assembly plants at a lower cost and faster speed [7]. In this way, the system can reduce both inventory cost and distribution cost, and thus decrease the product price.

Considering the actual situation of China's automobile industry, this paper pioneers the discussion of the multi-factory milk run pickup problem with uncertain demand and frequency (MFMRPP-UDF). In the logistics system, there are many assembly plants and numerous part suppliers located close to each other. The suppliers collect the parts and transport them to the assembly plants in the small-batch and multi-frequency mode, aiming to balance the inventory cost and distribution cost under uncertain demand.

The remainder of this paper is organized as follows: Section 2 reviews the relevant studies on our topic; Section 3 puts forward the mathematical formulation; Section 4 designs a detailed solution to the problem; Section 5 explores a specific case of the problem; Section 6 wraps up this paper with meaningful conclusions.

2. Literature review

In the automotive parts industry, the milk run problem can be considered as a special vehicle routing problem (VRP) [7]. So far, many variants of the VRP have been developed, but few of them tackle the balance between the VRP and transport frequency under uncertain demand.

Luiz *et al*. [8] were the first to introduce the milk run strategy to cut the number of cycles in lean manufacturing. Following the strategy, these scholars saved over 80 % of the inventory cost, and diverted the labour force on parts unpacking to production building, creating a truly smooth material flow. Sadjadi *et al*. [6] proposed a mixed-integer milk run method for supply chain problems, and designed a customized metaheuristic for a special case in the automobile industry. Jiang *et al*. [9] developed an optimization-based routing approach for a small-batch, multi-frequency JIT supply system, and presented a tabu search problem to solve the problem. Nevertheless, their approach only minimizes inventory cost and distribution cost of suppliers, failing to benefit the assembly plants or fulfil the uncertain demand. Lin *et al*. [10] applied a two-phase heuristic algorithm to handle the single-plant milk run pickup problem. As the name suggests, the algorithm merely considers a single assembly plant under certain demand. Focusing on a real-time milk run-based vehicle routing problem, Du *et al*. [11] proposed the best fit algorithm for initial vehicle dispatch and the 2-point crossover algorithm for inter route improvement, and determined the parameters of the problem through comprehensive experimental design. Klenk *et al*. [12] laid down various peak handling strategies to ensure the efficiency and stability of in-plant milk run systems.

In addition, some scholars have explored the dynamic milk run routing problem. For instance, Antonio *et al*. [13] investigated the milk run JIT production problem with occasional over-congestion, created a dynamic alternative for vehicles to perform extra tasks, and predicted urban traffic surges by probabilistic sequential analysis. Guner *et al*. [14] discussed the dynamic milk run routing with stochastic time-dependent networks, in which the travel times are stochastic and time-dependent due to the recurrent congestion. Specifically, these scholars generated dynamic routing policies through stochastic dynamic programming, and obtained the travel time distribution by simulation. Despite the consideration of uncertain factors, these studies take not account of the relation between inventory cost and distribution cost.

Cho *et al*. [15] introduced the inventory factor into vehicle route planning, creating the inventory routing problem (IRP). In pursuit of the minimum system cost, the IRP only attaches importance to inventory quantity and vehicle routing. Jiang *et al*. [9] probed into the common frequency routing (CFR) problem, aiming to minimize inventory cost and distribution cost. Focusing on frequency and routing, their solution only allows a vehicle to pay a single visit to each supplier, which is obviously irrational for the case of multiple assembly plants. Considering uncertain inventory, Jafari-Eskandari [16,17] developed a robust optimization solution to milk run system with time window, minimized the distribution cost for all inventories in a given bounded uncertainty set, and optimized the routes from the perspective of suppliers and logistic service providers (LSPs).

From the above analysis, it is clear that the MFMRPP-UDF problem has not been given much attention. To make up for this gap, this paper attempts to study this problem considering the balance between inventory cost and distribution cost. Specifically, a mixed-integer programming model was built for the problem, and converted into a robust optimization model by the Chernoff-Hoeffding theorem; then, the adaptive genetic algorithm (AGA) and local search (LS) were combined into a hybrid heuristic algorithm (AGA-LS) to solve the problem.

3. Problem formulation

3.1 Mathematical model

The MFMRPP-UD can be defined as directed graph $G = (V, E)$, where $V = D \cup N$, with $D = \{1, 2,\ldots, m\}$ being the set of assembly plants and $N = \{1, 2,\ldots, n\}$ being the set of part suppliers, and $E = \{(i, j): i, j \in V, i \neq j\}$ is the set of routes [18]. Let q_d, α_d, $[0, T]$ and β be the uncertain demand, unit inventory cost, operation period, and unit distribution cost, respectively, where $d \in D$. Besides, let c_{ij} and t_{ij} be the distance and travel time from i to j, respectively. For the part supplier $i \in N$, it is assumed that the load time is t_i, and the supply quantity is s_i. Let $K = \{1, 2,\ldots, k\}$ be the set of the vehicles, each of which has a capacity of Q. In addition, let us define f_k as the pickup frequency for the vehicle $k \in K$, and $p_{ik} = s_i/f_k$ as the part quantity picked up by the vehicle $k \in K$ at the supplier $i \in N$.

Then, the following decision variables were defined before setting up the mix-integer programming model:

$$x_{ijk} = \begin{cases} 1 & \text{the truck k travels from node } i \text{ to node } j \\ 0 & \text{otherwise} \end{cases}$$

$$y_{dk} = \begin{cases} 1 & \text{the truck k is assigned to depot } d \\ 0 & \text{otherwise} \end{cases}$$

$$z_{ik} = \begin{cases} 1 & \text{the truck k picks up at part supplier } i \\ 0 & \text{otherwise} \end{cases}$$

Thus, the model was constructed as:

$$\min\left\{\sum_{k\in K}\sum_{i\in V}\sum_{j\in V} x_{ijk}c_{ij}f_k + \sum_{k\in K}\sum_{i\in V}\sum_{d\in D}\alpha_d p_{ik} z_{ik} y_{dk}\right\} \tag{1}$$

$$\sum_{d\in D}\sum_{j\in V}\sum_{k\in K} x_{djk} \le K \tag{2}$$

$$\sum_{k\in K}\sum_{j\in V} x_{ijk} = \sum_{k\in K}\sum_{j\in V} x_{jik} = 1, \forall i \in V \tag{3}$$

$$\sum_{i\in D}\sum_{j\in D} x_{ijk} = 0, \forall j \in V, k \in K \tag{4}$$

$$\sum_{i\in V} x_{idk} y_{dk} = \sum_{i\in V} x_{dik} y_{dk} \le 1, \forall d \in D, k \in K \tag{5}$$

$$\sum_{d\in D} y_{dk} = 1, \forall k \in K \tag{6}$$

$$\sum_{i\in V} z_{ik} = 1, \forall k \in K \tag{7}$$

$$\sum_{j\in V} x_{ijk} = z_{ik}, \forall i \in N, k \in K \tag{8}$$

$$\sum_{i\in V} x_{ijk} = z_{jk}, \forall j \in N, k \in K \tag{9}$$

$$\sum_{i\in V} p_{ik} z_{ik} = Q_k, \forall k \in K \tag{10}$$

$$\sum_{i \in V} t_i z_{ik} + \sum_{i \in V} \sum_{j \in V} t_{ij} x_{ijk} \leq T, \forall k \in K \tag{11}$$

$$\sum_{i \in V} \sum_{k \in K} p_{ik} z_{ik} y_{dk} = q_d, \forall d \in D \tag{12}$$

$$x_{ijk}, y_{dk}, z_{ik} \in \{0,1\}, \forall i, j \in V, d \in D \tag{13}$$

In the above formulation, Eq. 1 minimizes inventory cost and distribution cost; Eq. 2 limits the total number of vehicles; Eq. 3 and Eq. 4 stipulates that a vehicle visits each part supplier only once; Eq. 5 requires that each vehicle must leave from and return to the same assembly plant; Eq. 6 guarantees the one vehicle is only assigned to one assembly plant; Eq. 7-9 defines the value of z_{ik}; Eq. 10 specifies the capacity of each vehicle; Eq. 11 sets out the operational period; Eq. 12 lays down the demand of each assembly plant; Eq. 13 provides the decision variables.

3.2 Robust optimization

Despite the uncertainty in the volume and time of the demand from assembly plants, the suppliers always expect the demand to be fulfilled at the minimum inventory cost and distribution cost. Thus, it is necessary to prepare a robust schedule according to the actual conditions. In light of this, Eq. 12 was transformed to depict the uncertain demand by means of a chance-constrained stochastic program based on possibility measure:

$$pr\left\{q_d - \sum_{i \in V} \sum_{k \in K} p_{ik} z_{ik} y_{dk} \geq 0\right\} \geq \varepsilon, \forall d \in D \tag{14}$$

where ε is the pre-set level of confidence. Then, the Chernoff-Hoeffding theorem [20, 21] was introduced to transform Eq. 14 into a robust constraint:

$$r_d = \left\{1 - 2exp - 2\left[q_d + E(\rho_d) - \sum_{i \in V} \sum_{k \in K} p_{ik} z_{ik} y_{dk}\right]^2 \div (u_d - l_d)^2\right\}, \forall d \in D \tag{15}$$

where $E(\rho_d)$ ($d \in D$) are the expected values of uncertain variables; $[u_d, l_d]$ ($d \in D$) are the internal values of uncertain variables.

4. Proposed methods

To solve the NP-hard MFMRPP-UDF problem, the AGA and the LS were combined into a hybrid heuristic algorithm (AGA-LS). The AGA is good at solving NP problems thanks to its robustness and global search ability [21, 22] while the LS is a desirable way to process diverse population and prevent local optimum trap [23-27].

4.1 Representation of solutions (coding)

The solution was represented as a double-layer chromosome coding program. The first layer contains the assembly plants, and the second layer stands for the routes. First, r routes were generated by greedy strategy (GS). For example, suppose there exists a solution involving 2 assembly plants and 12 suppliers with 4 routes r1 1-3-5-6-1, r2 1-9-11-13-1, r3 2-4-7-8-2, and r4 2-10-12-14-2 (Fig. 1). On each route, the vehicle leaves from and returns to assembly plants 1 and 2, respectively (Fig. 1).

4.2 Initial solutions

The initial solutions can be generated as follows described by Algorithm 1:

Algorithm 1: Initial solution generation
Input: Population size P; the set of unserved suppliers N'.
Output: Initial solution S

```
For count ← 1 to P do
S ← ∅, N' ← N
  if N' ≠ ∅ do
      Insert a supplier i selected randomly into the route of vehicle k by the GS
      N' ← N\i
   end
   S ← s
End
```

4.3 Improved 2-point crossover

In light of the features of multiple assembly plants, a 2-point crossover operation was designed below (Fig. 2):

- Select two chromosomes according to the crossover probability;
- Select two random gene positions $g1$ and $g2$ from chromosome $P1$;
- Switch the places of genes $g1$ and $g2$ with the genes $g3$ and $g4$ in the same position of chromosome $P2$;
- Switch the places of other genes in $P1$ in a similar way;
- Switch the places of other genes in $P2$ in a similar way.

Next, the adaptive crossover probability was used to select individuals:

$$p_c = \begin{cases} p_{c1} - \frac{(p_{c1}-p_{c2})(f'-f_{avg})}{f_{max}-f_{avg}}, & f' \geq f_{avg} \\ p_{c2}, & f' < f_{avg} \end{cases} \tag{16}$$

where f_{avg} is the mean fitness of the current population; f_{max} is the maximum fitness of the current population. Usually, p_{c1} = 0.9 and p_{c2} = 0.6.

4.4 Mutation operation

The author designed a simple mutation operation as follows (Fig. 3):

- Select a chromosome according to mutation probability;
- Remove a random gene from the chromosome;
- Insert the gene into another position of any other route randomly.

The adaptive mutation probability was adopted:

$$p_m = \begin{cases} p_{m1} - \dfrac{(p_{m1}-p_{m2})(f_{max}-f)}{f_{max}-f_{avg}}, & f' \geq f_{avg} \\ p_{m2}, & f' < f_{avg} \end{cases} \tag{17}$$

where p_{m1} = 0.1 and p_{m2} = 0.01.

Assembly plant	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
Route	1	3	5	6	0	9	11	13	2	4	7	8	0	10	12	14

Fig. 1 Double-layer solution representation

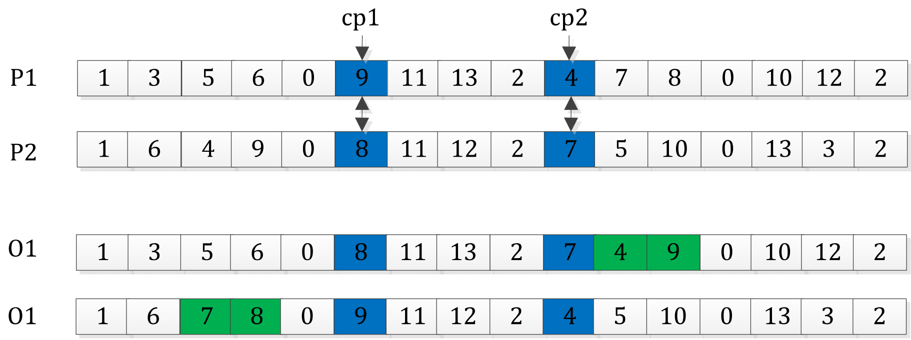

Fig 2 An example of 2-point crossover operation

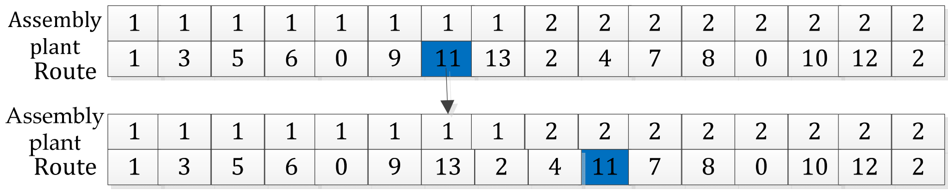

Fig. 3 An example of the muation operation

4.5 Selection

The individuals of relatively high fitness were copied to the next generation. Here, the roulette wheel method is employed for the selection of these individuals. During the iteration, some infeasible solutions may occur, which helps to explore better solutions. Hence, the objective function was combined with a penalty function into the fitness function below:

$$F_{fit}(I) = F(I) + W(I) \tag{18}$$

where $F(I)$ is the objective function; $W(I)$ is the penalty function:

$$W(I) = \alpha_1 w_1 + \alpha_2 w_2 \tag{19}$$

$$w_1 = max\left\{\sum_{i \in V} p_{ik} z_{ik} - Q_k, 0\right\} \tag{20}$$

$$w_2 = max\left\{\sum_{i \in N} t_i z_{ik} + \sum_{i \in V}\sum_{j \in V} t_{ij} x_{ijk} - T, 0\right\} \tag{21}$$

4.6 Local search

The LS can promote the quality of global search, and enhance the final solution [28]. In light of our problem, two neighbourhood structures were created to search for new solution spaces:

- Exchange operation: Select any chromosome and switch the places of any two genes on the chromosome;
- 2-opt: Reverse the order of any two genes in a random chromosome.

5. Case Study: Results and discussion

This section applies the proposed formulation in a real case using Python. The application was run on a computer (1.8 GHz Intel Core, 4 GB RAM). The CMAL, a third-party logistic provider for automobile enterprises, was taken as the object of the case study. The CMAL currently serves two assembly plants. The basic parameters are as follows: vehicle size is 2.4 × 2.4 × 9.6 m^3, unit distribution cost is 4.7, and inventory cost is 2. The data on demand and location of assembly plants are listed in Table 1, and the data on supply and location of suppliers are listed in Table 2. For assembly plant 1, the uncertain demand obeys normal distribution in [0, 9] and the expected value is 911.16; for assembly plant 2, the uncertain demand also obeys normal distribution in [0, 9] and the expected value is 782.62. The maximum and minimum values of uncertain variables were determined by the 3 σ rule.

The AGA-LS is run 10 times with the frequency 6, 7, 8, 9 and 10 when the demand is certain, the largest and smallest frequency numbers are obtained according to the production planning. The cost changes as follows in Table 3.

We can find that the cost is lowest when the frequency is 6. In this case, the inventory cost is 564.6, and the transportation cost is 2491.5. when the frequency increases from 6 to 10, the transportation cost also increases from 2491.5 to 3435.1, but the inventory cost decreases from 564.6 to 338.8. we can conclude that the transportation cost increases more than the inventory cost as the frequency increases. The cost change of the Instance 1 with the iteration is seen in Fig. 4. We can find that our proposed algorithm has a high convergence speed where a better solution is obtained when the iteration reaches no more than 60. In addition, when the iteration ranges from 0 to 60, the solutions are improved greatly and fast, which validates the superiority of the algorithm on solving the problem.

Table 1 Data about 2 assemble plants

ID	Demand	Coordinate_x	Coordinate_y
1	911.16	106.538078	29.677212
2	782.61	106.596291	29.68965

Table 2 Data about suppliers

ID	Supply	Coordinate_x	Coordinate_y
1	90.04	106.514381	29.669697
2	226.10	106.515114	29.664557
3	135.39	106.508034	29.667334
4	5.29	106.502769	29.666943
5	85.48	106.499321	29.664776
6	84.66	106.498947	29.666237
7	61.62	106.531982	29.683313
8	85.40	106.535172	29.681656
9	63.87	106.534164	29.680086
10	31.74	106.592857	29.675314
11	18.42	106.599693	29.679518
12	23.50	106.591721	29.678984
13	17.66	106.594559	29.68322
14	34.42	106.596855	29.685228
15	38.49	106.587585	29.684204
16	124.62	106.601219	29.691582
17	87.04	106.601578	29.694155
18	90.91	106.597221	29.694084
19	170.53	106.600243	29.698023
20	85.48	106.59433	29.6973
21	133.11	106.589554	29.696985

Table 3 Cost changes with different frequencies

	Frequency				
Instance	6	7	8	9	10
1	2864.5	2806.1	3733.8	3433.0	4042.0
2	2980.8	3443.2	3837.1	4227.3	3436.0
3	3263.7	3455.9	2884.0	3909.8	3986.0
4	2990.4	3158.2	3686.2	3867.9	3337.0
5	3156.0	3358.8	3564.9	3139.5	3475.5
6	3245.1	2884.8	3816.4	4133.1	3425.8
7	3082.0	3026.5	3264.0	3879.5	4539.0
8	2913.6	3520.7	3348.1	3121.5	3880.1
9	2803.1	2852.5	3657.8	3229.6	4174.4
10	3261.4	3523.2	3558.6	3244.7	3443.5
Average cost	3056.1	3203.0	3535.1	3618.6	3773.9

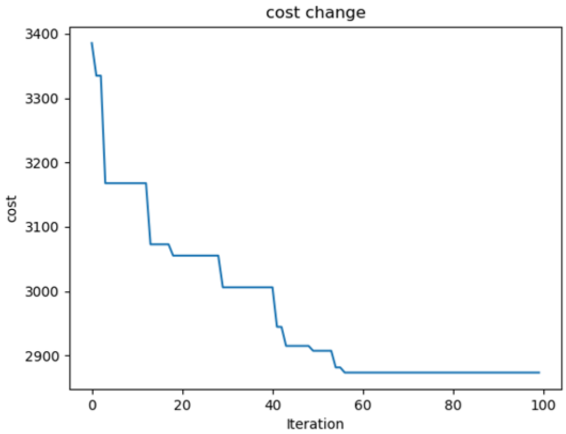

Fig. 4 the cost change with the frequency 6

Next, the AGA-LS is compared with the standard GA at the frequency of 6. The results are shown in Table 4.

We can conclude that we can get a better solution with total average cost 3056.1 by means of AGA-LS, and the total cost is 3786.7 obtained by the means of GA, the savings is over 20 % on average, which demonstrates the superiority of our method.

For the robust optimization model, defining the values of robust levels is important. However, schedulers cannot determine exactly the values of these variances. In this paper, we assume the robust level is 0.8. According to above analysis, the total cost is lowest when the frequency is 6. We can get following transportation schedules that is seen in Table 5.

According to the probablity distribution of uncertain demand, we generate 10 isntances with uncertain demand (the demand ranges from 902.16 to 920.16 at the depot 1 and from 773.61 to 791.61 at the depot 2) to evaluate the solutions. There are 10 routes on each schedule. As a result, we find 27 of 100 routes cannot satisfy the demand of corresponding assembly plant on the optimal schedule, while only 10 of 100 routes cannot satisfy the demand of corresponding assembly plant on the suboptimal schedule. We can concluside that the suboptimal schedule is a more stable one though its total cost is higher. Therefore, the manager can do that trade off between schedule stability and schedule cost according to obtained results and their production plan, e.g. they can apply the stable schedule for the sale season and the low cost schedule for the slow season.

Table 4 Performance analyze between AGA-LS and GA with the frequency 6

	Instance										
	1	2	3	4	5	6	7	8	9	10	Average
AGA-LS	2864.5	2980.8	3263.7	2990.4	3156.0	3245.1	3082.0	2913.6	2803.1	3261.4	3056.1
GA	2957.4	4471.2	3590.1	5382.7	3534.7	3991.5	3236.1	3117.6	3215.6	4370.3	3786.7

Table 5 Comparison of Optimal and suboptimal schedules

Transportaton schedule	Route		Objective value	Acceptable degree
Optimal schedule	Depot1 : D1-3-5-6-D1 D1-7-18-19-17-16-10-D1 D1-1-2-D1 D1-9-D1 D1-8-D1	Depot2 : D2-9-D2 D2-21-17-16-11-14-13-D2 D2-15-12-D2 D2-7-4-3-D2 D2-18-19-20-D2	2803.1	73/100
Suboptimal schedule	D1-5-6-D1 D1-7-9-D1 D1-1-3-2-D1 D1-8-D1 D1-18-19-17-16-10-D1	D2-17-16-11-D2 D2-18-20-21-D2 D2-14-3-D2 D2-9-7-D2 D2-15-12-13-14-19-D2	2933.1	90/100

6. Conclusion

This paper developed a novel model for milk run pickup problem on the distribution of automobile parts. Considering the complexity of the problem, the AGA-LS solution method was developed through the integration of the AGA and the LS. The proposed algorithm was run 10 times and contrasted with the standard GA. The results show that the AGA-LS outperformed the standard GA in the reduction of the overall cost.

This paper marks the first-ever research into the VRP on milk run pickup problem with uncertain demand and frequency, considering the balance between inventory cost and distribution cost. Our solution method is of important practical significance for logistics enterprises and automobile enterprises to make plan. The research findings also lay a solid foundation for the survey on stochastic travel time and the time windows, which will be the further research direction to make our proposed solution method more practical. In addition, order to guide operations of enterprises, we will develop a vehicle dispatch platform.

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Application of structural equation modelling to analyse the impacts of logistics services on risk perception, agility and customer service level

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A B S T R A C T

Logistics services of manufacturing enterprises help to improve transport, delivery of materials and finished products. This paper presents a causal model to identify the influence that has the availability of logistics services on the risk perception, on agility and on customer service level of manufacturing companies. A questionnaire was developed, validated and applied to 225 employees of different industrial sectors. Information is integrated in a structural equation model for test seven hypotheses using partial least squares to calculate the regression coefficient between variables using 95 % confidence level. The results mainly indicated that the availability of logistics services have a positive and direct effect on risk in demand and in supplier's risk; but in addition, agility and transportation also have effects over them. All these variables have direct or indirect contributions on customer service level and can explain 45 % of its variability. On the other hand, it is also identified that transportation performance has a direct effect on agility 0.42 standard deviation units. Findings in this paper demonstrate quantitatively through a statistical analysis the importance of infrastructure for logistic services available in the regions, the role of transportation and its impact on risk in suppliers and agility, and how customer services can be improved increasing supply chain agility and diminishing the risk in demand.

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A R T I C L E I N F O

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1. Introduction

Amid economic globalisation and the increasing complexity of economic relationships, companies currently require certain methodologies and techniques to improve and defend their positions within a global market [1]. Nowadays, the abilities to respond to challenges such as the continuous and rapid changes in customer demands, and remain competitive are critical success elements for modern organizations. Supply Chain (SC) is a network of companies interconnected by different kinds of flows: financial, materials, and information between suppliers to customers. Therefore, these organizations depend on their modernisation and globalisation to increase their competitiveness [2]. In this manner, they focus on mastering changing markets by being competitive in on-time product delivery at low costs and high quality with short cycle times. That is, they still seek high levels of customer service.

The goal of SC is to manage the selection of material resources, suppliers, manufacturing process, delivery of products to the end user in such a way that products will move through the network of business activities in the small period and with least input. However, the achievement of this goal requires of assessing the connection between logistics services and suppliers in order to detect potential flaws that may compromise supply chain performance (SCP). Moreover, it can be said that under current conditions, practically there is no company in the world that can be operating in a complete secure environment. Risks have become the main concern in logistics and business processes [3]. From this perspective, SC risk is viewed as a number of unreliable and uncertain resources creating interruption, whereas uncertainty can be explained as matching risk between supply and demand in SC processes [4], and it tends to affect SCP. The stability of the SC depend of capacity of disruption classification to implement corrective actions in time [5], that improvement their results. Risk in demand is perhaps the most serious risk. It arises from volatile demand or inaccurate forecasts. In addition, the greater the risk in SC is, the poorer its performance becomes (inventory costs, lead time, agility, flexibility, and customer service). Hence, communication and the integration of suppliers with manufacturing companies are critical to make appropriate changes in costumers' needs and achieve high levels of customer service [6]. Similarly, to integrate all processes in a SC offer different opportunities of businesses, nevertheless this may imply many challenges, such as the establishment of key risk management objectives [1]. The key element, however, in on the flexibility and agility of all processes, and a modest idea of current state involves even a resilient focus on cooperative and integrative activities under the endowment of a better monitoring and connection through infrastructures of communication and information technologies (IT) [7].

First, flexibility is becomes an important instrument of competitiveness in global market and according Christopher [8] it constantly increases the number of organizations that choose it as mechanism of competitiveness [7]. Similarly, recent decade tendencies show that customers are demanding for wider variety of goods proposed and further possibilities for individual satisfaction of needs [9]. These challenges force organizations to become more flexible, adapt not only to global market in regard to prices and term, but to adapt to the changing demand in the market also. The most common direction of the research in this field is to evaluate flexibility of process in coordination within SC, especially in practical level. Flexibility is contextualized as the ability that have the companies to adjust to changes of market to produce diversity of products, high levels of production volume, or specific designs [10]. SC flexibility implies to produce different and new sophisticated non-standard products corresponding particular needs of consumers; to produce the orders for different volumes, i.e. management of output volumes; to use alternative methods by transferring all instruments needed for future work to the adequate location; to be adapted to the changes while transferring is being made; to supply the available products to the consumer. SC flexibility is the ability to satisfy consumers' needs and expressed as the possibility to supply different products, production quantities, and variety of new products and availability of products to consumer as response to market demand, with the purpose of acquire or preserve competitiveness. Often SC agility is described as ability to respond to short-term changes of demand or supply. In the other hand, the concept of agility was originated in the manufacturing sector in the early decade of 1990. It is defined as "the ability of a company to rapidly adjust tactics and operations within their SC and respond or adapt to changes, opportunities, and threats in their environment"[6]. Additionally, SC agility is as ability of a firm for handling the changes of volume and variety of products to satisfy the customer demand [11] , and was tightly associated with the effectiveness of strategic SC management in the competition among supply chains, rather than entities. The agility has two dimensions, alertness to change and response capability, at three levels: strategic, tactic and operational. Constantino *et al.* [12] defined it as a network of diverse companies integrated by materials, information, and financials flow, and focused on add value to improvement the flexibility and SCP. On the one hand, improving agility demands the contribution of information, communication, and coordination through information systems, infrastructure, and availability of logistics services [7]. In this manner, transportation and logistics services by themselves are also important for competitiveness; thus, their impact must be assessed. Studies have evaluated different types of logistics services, such as road, railway, air, and maritime, including the analysis of costs in transport infrastructure, business services, and telecommunications. The availability and quality of these services have become important factors in the development of competitive strategies, although it has been proved that customer service is also crucial for the economic development of any region [13]. One critical components to effectiveness of logistics services is the support given by the information technology systems, since they is possible that have impacts on logistics operations. For instance, they facilitate cooperation and collaboration among SC partners and enable the automation of many logistics routine activities; these factors have been analyzed in different companies [14].

However, there is still a lack of empirical studies regarding the impact of availability services and transportation on SC agility in maquiladoras. Maquiladoras are, in fact, a type of company exports its finished products but imports raw materials and/or components from other countries. In Mexico, they share a highly competitive manufacturing platform with the United States of America and Canada [15]. Moreover, during the last 45 years, Mexican maquiladoras have become an important element to the economy of Mexico. The structure of this type of companies is that they belong to a global SC, so the requirements for improvement in the logistics and operations processes are high. Therefore, to contribute to the discussion of the impact of logistic services level on SC performance, this paper seeks to measure the influence of availability of logistics service on risk in supplier and risk in demand, agility and customer service level.

2. Methodology

2.1 Questionnaire and survey design

As methods, a questionnaire for gathering data was designed. It includes four major sections, and based on the research findings described by Bhatnagar and Sohal [7]. According activities and SC benefits in manufacturing industries operating in Asian countries like Singapore, Malaysia, Brunei, Indonesia, Philippines, and Thailand were listed. These activities include: evaluation of risk in demand, evaluation of risk in supplier, evaluation of logistics services, and transportation. Additionally, the most relevant benefits obtained from these activities respect to results of agility and customer service were also identified. The proposed questionnaire was adapted to identify similar elements in manufacturing industries of other countries including Mexico with the purpose of finding results about their performance and needs of improvement and development.

Selection and identification of the activities and elements of performance

Once a literature review was accomplished, the elements and the activities from logistics services, risk in supplier and risk in demand were identified. On the one hand, the elements of performance were determined and Table 1 shows the four elements surveyed. They were analysed as independent latent variables and include *Logistics services* (LSer), *Transportation* (Tran), perception of *Risk in demand* (DRisk), and *Risk in supplier* (SRisk). The same table also introduces the activities related to these elements and the literature that has addressed to them. However, these activities were adapted to the context of the research and validated for others authors since they come to an agreement on the importance of the same activities; the items related with the risk in suppliers (SRisk1, SRisk2, SRisk3, SRisk4) also are shown to evaluating contributions in SCP as well Bhatnagar and Sohal [7]. On the other hand, Table 2 introduces the benefits surveyed: agility (Agil) and customer service (CSer). The literature focusing on these benefits is also included in the table (brackets), i.e. customer service in terminus of complete orders, best rate of complete orders, and timely responds to customer needs. On the other hand, Table 2 also includes agility as an aspect of supply chain performance Finally, since some of the items of the questionnaire to assess the availability of logistics services in the region, to considered it as regional elements to increases competitiveness of firms established in a given city or region.

In addition, the questionnaire contains one section about demographic data of participants, this helps identifying the industrial sector and other characteristics of the studied population and characteristic of the sample. Items were integrated in questionnaire, and a response validation was carried out to ensure their understanding. Hence, a preliminary test was administered to managers, supervisors, and academics, and it was responded in a Likert scale for subjective assessments, with a rating range from of 1 to 5; moreover, items of Table 1 and Table 2 defined the hypotheses proposed for the model shown in Figure 1, which are the corresponding items to latent variables from structural model (causal model). Some authors have relied on this scale in their studies of SC environments [26].

Table 1 Items of the construct of "Logistic activities"

Risk in Supplier (SRisk)	a	e	f	g	h	i	j
(SRisk1) My suppliers always deliver on-time orders.	x	x	x	x	x		x
(SRisk2) My suppliers always deliver complete and accurate orders.	x	x	x	x	x		
(SRisk3) My suppliers always deliver products according to quality standards.	x	x	x	x	x		
(SRisk4) My suppliers always remain in communication to reduce failures.	x	x	x	x	x		
Risk in Demand (DRisk)							
(DRisk1) Demand is always communicated in advance to the company by…	x					x	x
(DRisk2) Demand is transmitted by clients through real-time information systems…	x					x	
(DRisk3) Demand is visible in real time for both the company and its suppliers.	x					x	
(DRisk4) Demand for the finish product is stable and does not affect the demand…	x					x	
Logistics Services (LServ)							
(LServ1) Availability of air, road, maritime, financial, and legal services, and…	x			x			
(LServ2) Quality of air, road, maritime, financial, and legal services and…	x			x			
Transportation (Tran)							
(Tran1) Costs from raw materials and products transportation are low.	x						
(Tran2) Transportation units with satellite tracking systems have improved delivery	x						
(Tran3) Quality of transportation has improved in the last 3 years thanks to…	x						

a:[7]; b:[13]; c:[16]; d:[14]; e:[17]; f:[18]; g:[19]; h:[20]; i:[21]; j:[22]; k:[23]; l:[24]; m:[25]

Table 2 Items of the dimensions of the questionnaire correspond to benefits of performance

Agility (Agil)	a	b	c	d	h	i	k	l	m
(Agil1) Time for product development has improved in the last 3 years…	x	x	x			x	x		
(Agil2) Time management has improved in the last 3 years in relation…	x	x	x			x	x		
(Agil3) The company effectively responds to unexpected customer…	x	x	x			x	x		
(Agil4) Levels of product customisation have increased.	x	x	x			x	x		
(Agil5) The company meets the delivery capabilities required by the…	x	x	x			x	x		
Customer service (CSer)									
(CServ1) In general, the company has successfully completed orders in…	x			x	x		x	x	x
(CServ2) In comparison to other companies from the same industrial sector…	x			x	x		x	x	x
(CServ3) Company timely responds from customer needs.	x			x	x		x	x	x

a:[7]; b:[13]; c:[16]; d:[14]; e:[17]; f:[18]; g:[19]; h:[20]; i:[21]; j:[22]; k:[23]; l:[24]; m:[25]

2.2 Survey administration and data collection

The sample for this study was stratified, and it mean considered only the 326 (in 2017) maquiladoras established along the Ciudad Juarez. Then, a simple random sample of companies was selected as potential participants. The application of questionnaire was support by "University's APICS-UACJ chapter", and was done using three strategies to administer it; first, personal interviews were carried out; second, participants also had the opportunity to receive the document by their email, and finally, the questionnaire administration through an online specialized platform where the proper the link was sent to the respondent also by email.

2.3 Data capturing and validation

Information obtained was captured and analyzed by using software SPSS 21®. This was made to develop a descriptive analysis of the information about, gender, industrial sector, experiences of participants, etc. Missing values were detected and substituted by the median value of items, since data were obtained of an ordinal scale [26]. Also, outliers or non-typical values were identified to standardize every variable and internal consistency or reliability of every latent variable was assessed by using Cronbach's alpha and composite reliability indexes, considering a cutoff values of 0.7 for both [27]. However, some tests were additionally performed to improve reliability of the dimensions. Moreover, the average variance extracted (AVE) index was used as an indicator of both discriminant and convergent validity, using an acceptable value of 0.5 [28]. However, correlations among latent variables were also considered to assess convergent validity. Furthermore, full collinearity or the variance inflation factor (VIF) was employed to detect possible collinearity issues among latent variables. The rule of thumb of using a value of 3.3 as the maximum value was applied, although some authors suggest some higher than 10; Q^2 coefficient was used to assess nonparametric predictive validity (or relevance) with 0 as the minimum acceptable value.

2.4 Proposal and evaluation of structural equation model

This research seeks to analyse the impacts among the latent variables shown in Figure 1, which are measured by several items (Table 1 and Table 2). With structural equation modelling is possible to find a causal relationship between them and determine the contribution rate for each variable include in the model. The following paragraphs explain the justification for the formulation eighth hypothesis shown in the Figure 1, and graphically summarizes the proposed model. Transportation is a main part of the logistics processes and in the proper supply chains management. The main reason is because due to the fact that flows of products are globally shared and involves multiple companies. In this sense, the performance of the transportation is a key element for a good SCP. When failures or interruptions occur during the *Transportation* elements due to different causes that temporarily stops the passage of materials or products affecting the SCP [28], there will be a major perception of *Risk in Supplier*. The *Transportation* should encompass not only operations efficiency parameters, but also measures of service effectiveness to meet the goals of all parties, parties involved in the transportation logistics processes and the overall SCP. From this viewpoint, we propose three hypotheses to *Transportation* (Tran):

H1: The *Transportation* performance has a direct and positive effect on *Risk in Demand* (DRisk).
H2: The *Transportation* performance has a direct and positive effect on *Agility* (Agil).
H3: The *Transportation* performance has a direct and positive on *Risk in Supplier* (SRisk).

Logistics services, such as road, railway, air, and maritime, including the analysis of costs in transport infrastructure, business services, and telecommunications are important aspects to achieve competiveness and to improvement SCP [13]. These elements can be made up from an infrastructure perspective to improve of communication among companies. It required that companies and managers consider the ability to achieve effective communication with its suppliers and customers through the technologies used; this is the bottom line for promptly to reducing risk perception. It is also in line with the assertion that external integration with key suppliers is conducive to agility [11]. In this sense, two hypothesis are proposed regarding *Logistic services* (LServ):

H4: The *Logistic services* have a direct and positive effect on *Risk in Demand*.
H5: The *Logistic services* have a direct and positive effect on *Risk in Supplier*.

Risk sometimes is understood as unreliable and ambiguous resources that creates SC interruptions, whereas uncertainty can be explained as matching the risk between supplier and demand in SC processes. The risk in: supplier, information flow, material flow and product flow, are focusing on a specific function or as a part of a SC, and do not span across the entire chain. Risks affecting suppliers and also affecting customers [22]; i.e. risk in demand, logistics risk, risk in supplier and risk in transportation [16]. Additionally, SC agility creates value within firms through the cost efficiency, which can be achieved through logistics activities to enhance profitability, sales turnover, and customer satisfaction [29, 30]. The manufacturers SC agility should seek for opportunities for operational collaboration and management practices and strategies to performance [31] with their potential partners, such a relational factor is a driving force of satisfaction and performance with their suppliers. From this perspective, three hypothesis are proposed:

H6: The *Risk in Supplier* has a direct and positive effect on *Agility* (Agil).
H7: The *Risk in Demand* has a direct and positive effect on *Customer service* (CServ).
H8: The *Agility* has a direct and positive effect on *Customer Service* (CServ).

In order to determine the model´s fit indicators, the proposed hypotheses in Fig. 1 had to be validated by considered the direct effects between latent variables (arrows directly connecting) and estimated P-value. *Agility* and *Customer Serv*ice are SCP elements, and they derive from the interaction between *Logistics services*, *Transportation* and *Risk in Supplier* and *Risk in Demand*. To test hypotheses shown in Fig. 1, we used structural equation modelling in WarpPLS 5.0 software. This is based on partial least squares (PLS) algorithms, and it is widely recommended for small-sized samples [32]. Therefore, execution conditions were made by the WarpPLS4 algorithm with bootstrapping as resampling method for better convergence coefficients. Likewise, the Adjusted R-squared (Adjusted R^2) and Average Path Coefficient (APC) were the indices used to validate the model. On the one hand, ARS determined the model efficiency and APC determine the predictive validity with maximum cutoff P -value lower than 0.05. Also, the index Average block Variance Inflation Factor (AVIF) was analyzed to measure collinearity among latent variables, the rule of thumb was 3.3 as the maximum value [33], while Q-squared (Q^2) coefficient was used to assess nonparametric predictive validity (or relevance) with 0 as the minimum acceptable value. In order to determine the model's fit, the proposed hypotheses had to be validated by considered the direct effects between latent variables (arrows directly connecting) and their estimated P-value. Afterwards, indirect effects between variables were measured (given between two latent variables through a third path or more), also total effects (sum of direct and indirect effects). The significance of every effect was measured using its P-value, and the equations to the null hypothesis: βi equal to 0, and the alternative hypothesis: βi different to 0. Every hypothesis were tested using a confidence level of 95 %, and it could be included in the final structural model. The β value represents the relationship between variables and indicates a unit change in the dependent variable [34].

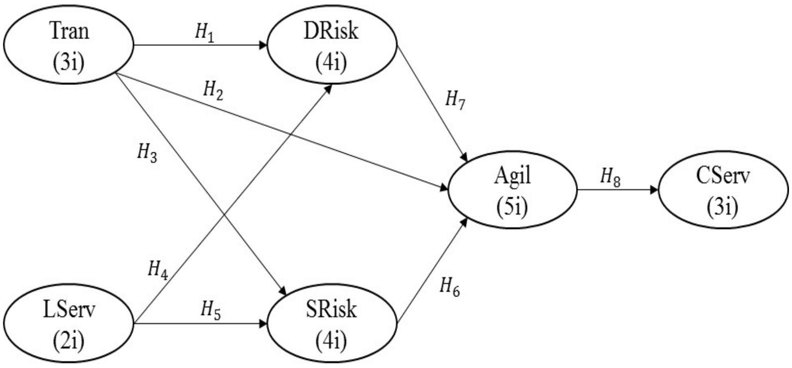

Fig. 1 Hypotheses from the relationship proposer in the model

3. Results and discussion

3.1 Sample description and analysis

After completing the process of data collection, it can to achieve the participation of 65 companies and 225 valid questionnaires were considered as a representative sample. Table 3 presents the results concerning the gender of respondents as well as the industrial sector of the surveyed companies. For instance, 156 participants were man and 58 were women. Also, 54 respondents worked in electronic sector, 39 in medical sector, and 67 in automotive sector. Please note that 11 participants did not specify their gender or job sector, this amount corresponding to 4.88 % of whole sample.

Table 4 presents the details of work seniority (expressed in years) and job position of respondents. First it can be observed that 46 participants have experiences level more than ten years in their current job positions, while the remainder (90 participants) reported between 4 and 10 years. Unfortunately, 20 individuals did not provide this information. Additionally, it can be observed the 54 held managerial positions, these participants represent 24 % of the complete sample size. Table 4 showed merely three participants worked as operation directors, while 11 did not report such information. It can be seen that both managers and planners have over two years of experience, and in some cases up to ten years, this indicates a good level of knowledge among respondents; and that the sample was composed mostly by individuals well informed about with SC.

Table 3 Gender of participants and industrial sector

Industrial Sector	Gender			Total
	Male	Female	Unspecified	
Automotive	45	21	1	67
Medical	24	12	3	39
Plastics	5	1	0	6
Metals	3	3	0	6
Electronic	43	9	2	54
Packing	2	0	1	3
Communications	0	1	1	2
Services	9	1	0	10
Others	19	9	2	30
Consumables	6	1	1	8
Total	156	58	11	225

Table 4 Positions and work experience of participants

Job	Years						Total
	0-1	2-3	4-5	6-10	>10	Unspecified	
Director	0	0	1	1	1	0	3
Manager	3	11	12	10	17	1	54
Engineer	4	2	4	6	2	0	18
Supervisor	4	16	5	6	8	1	40
Specialist	3	1	1	3	1	0	9
Technician	6	3	7	2	6	0	24
Operator	1	2	2	1	0	1	7
Planner	3	17	11	12	7	0	50
Unspecified	1	1	2	4	4	8	20
Total	25	53	45	45	46	11	225

3.2 Data reliability and validation

Table 5 presents the indexes of validation for latent variables in the model. From evaluation the reliability was considered the standardized loadings of every individual item of the questionnaire. According the values of Table 5, the information gathered is valid and can be used for its interpretation, are accepted since the values obtained are greater than 0.7, a recommended value to evaluate the internal consistency of the items in a construct (Cronbach Alpha Index: CAI), in addition, also the values showed an AVE higher than 0.5, these values confirm the discriminant and convergent validity presents in the questionnaire. The values for R-squared (R^2) are bigger than 0.15, which indicates predictive reliability, and Q-squared (Q^2) coefficients were similar to R^2 coefficients and upper than zero, hence indicating nonparametric predictive validity. On the other hand it can be seen that there is no evidence to declare collinearity among variables, because the results of the VIF are lower than the cutoff of 3.3 (maximum acceptable value for this research); all values in Table 5 are below to 2.

Table 5 Validation index of latent variables

Index	LServ	CServ	SRisk	DRisk	Agil	Tran
R^2 coefficients		0.451	0.158	0.164	0.282	
Adjusted R^2 coefficients (AR2)		0.446	0.150	0.157	0.276	
Composite reliability	0.941	0.857	0.888	0.888	0.909	0.848
CAI	0.874	0.750	0.831	0.831	0.874	0.730
Average variance extracted (AVE)	0.888	0.667	0.665	0.665	0.666	0.652
Full collinearity (VIF)	1.131	1.826	1.387	1.453	1.973	1.315
Q^2 coefficients		0.454	0.156	0.164	0.278	

3.3 Analysis and results: Structural equation model

The model validation and the fit indexes appear in Table 6. The whole model with the following values: APC = 0.305 with a P-value < 0.001, ARS = 0.264 with a P-value < 0.001, and an AVIF = 1.092, which was acceptable, since it was lower than 3.3. Finally, Tenenhaus GoF index for causal model achieved was 0.430, and this value is considered as large fit because is major to 0.36, for this index is recommended as minimum acceptable value 0.10. Note that the GoF index evaluates the goodness of fit of model about data provided. Therefore, it can be said that the adjustment of the data in relation to the proposed model is good, that because such relationships between variables happen in reality within companies as they are considered important for higher profits financial enterprises.

Table 6 Efficiency indices structural model

Index	Value	Decision
Average path coefficient (APC)	0.305	P < 0.001
Average R^2 (ARS)	0.264	P < 0.001
Average adjusted R^2 (AARS)	0.257	P < 0.001
Average block VIF (AVIF)	1.092	Ideal <= 3.3
Average full collinearity VIF (AFVIF)	1.514	Ideal <= 3.3
Tenenhaus GoF (GoF)	0.430	Large >= 0.36

Direct effects: they are causal relations basics or relations of variation that involving two variables. The direct effects are those that directly influence of one variable over another [35]. Figure 2 illustrates the causal model and the effects findings in the relations proposed and evaluated. That is, every segment has a dependence β value and a P-value from the significance test. It can be observed that dependence among variables initially proposed is valid, since every P-value is lower than 0.01. For example, these values of P-value indicate that the parameter evaluated is different of zero and, consequently, β is significant. The aforementioned indexes hence demonstrated that the model was valid and could be interpreted. For instance, according to Figure 2, the relationship between the *Transportation* (*Tran*) and *Agility* (*Agil*) has a dependency measure of β = 0.42. This means that when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable also increases by 0.42 units. Since it is a high-dependency relationship, it can be concluded that the appropriate *Transportation* of materials and products is crucial to increase SC *Agility*. The biggest β parameter among variables is given between SC *Agility* and *Customer service* with β = 0.58 and a P-value < 0.001, these values indicate that exits a high dependence among both variables, and it means that while response giving the companies to improve and promote agility activities on SC, they will provide higher levels of service to their customers. All direct relationships can be similarly interpreted. Moreover, note in Figure 2 that all dependent latent variables show a R^2 value. This value indicates the percentage of their variance that can be explained by other independents latent variables. For example, the dependent variable *Agil* has a $R^2 = 0.28$, and this is the extracted variance by the *Transportation* (*Tran*) and perception of *Risk in Demand* (*DRisk*). There is the 28 % of variance extracted to *Agil* is explain only from *Tran* and *DRisk*. Likewise, dependent latent variable about the *Customer service* (*CServ*) has $R^2 = 0.45$, indicating that SC *Agility* (*Agil*) is 45 % responsible of its variance; it is the highest value in R^2. This means that with an increment of standard deviation by 1 unit in *Agil* and in *DRisk* is possible improvement CSer; which is important because the elements create up these variables.

Indirect effects: they are causal relationships that involve the presence of three or more variables. There is an indirect relationship among two variables when a third modulates the effect between the first two, i.e., when the effect between the first variable and the second passes through the third. The existence of an indirect effect among two variables does not cancel out the possibility that there is likewise a direct influence between them.

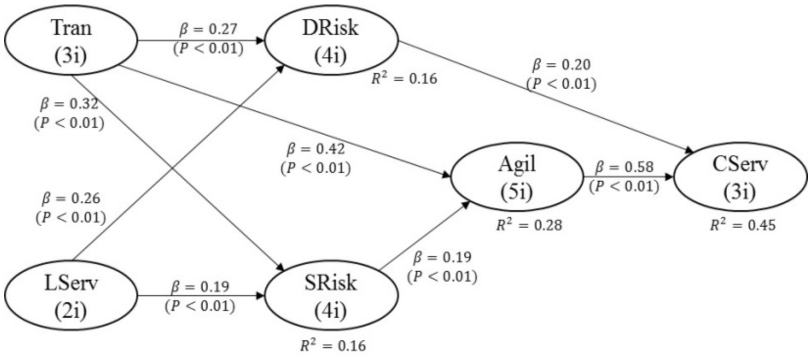

Fig. 2 Structural equation model final and significant relationships found

Indirect effects to one, two and three segments: For instance, based in the Figure 2, there are three indirect effects between latent variables *Logistics services* (*LServ*) and *Customer service* (*CServ*) given though *Risk in Supplier*, *Risk in Demand* and *Agility* (*SRisk*; *DRisk; Agil*) respectively. This indirect effect occurs through three segments.

Table 7 also there is an indirect effect between the *Transportation* (*Tran*) and customer service (*CServ*), corresponding to indirect effect of two segments. Initially, the indirect effect of this relationship is given by only one segment: either perception of *Risk in Demand* (*DRisk*) or *Agility* (*Agil*); finally, the relationship between *Transportation (Tran*) and *Customer service (CServ)* occurs through two segments: *SRisk* and *Agil*. The result of this effect is the sum from both indirect effects (one and two segments); first, is multiplied the effect between *Tran* and *Agil* (0.420) with the effect between *Agil* and *CServ* (0.581), that is, (0.581 × 0.420 = 0.244); second, is multiplied the effect between *Tran* and *DRisk* (0.272) with the effect between *DRisk* with *CServ* (0.201), that is, (0.271 × 0.201 = 0.054); and with the values finding the result is 0.244 plus 0.054, obtained a value of 0.299 showed in Table 7. The indirect effects to three segments are calculus similarly, but it considering other variable; for example, the indirect effect of *Logistics services* (*LServ)* in *Customer service* (*CServ)* is given for perception of *Risk in Supplier (SRisk)* and the *Agility* (*Agil)*. The result of this is the multiplication of all effects: *LServ* on *SRisk*, *SRisk* on *Agil*, and *Agil* on *CServ* (0.188 × 0.194 × 0.581, respectively), and obtained a value of 0.0211 shows in Table 7 (marked). Additionally, Table 7 presents the indirect effects for every relationship between latent variables as well as their P-values for the significance assessment and also displays the results of indirect effects for two and three segments. These effects are calculated by multiplying each contribution of the variables involved in the chosen path. For example, the *Risk in Supplier (SRisk)* has an indirect effect of 0.113 to *Customer service (CServ)*, which is by an effect of *SRisk* to *Agil* with value of 0.194, and another effect of *Agil* to *CServ* with value of 0.581 (0.194 × 0.581 = 0.1127, approx. 0.113). The value for this effect indirect is marked whit gray and corresponding to indirect effect of two segments. Since the relationship has a value of 0.113, it is implied that when the *Risk in Supplier* (*SRisk*) increases its standard deviation by one unit, the standard deviation of *Customer service* (*CServ*) rises by 0.113 units. Thus, it is proved that the reduction of *Risk in Supplier* improves *Customer service* and thus satisfaction. Likewise, low perception of *Risk in Supplier* helps prevent production stoppages due to a lack of raw materials. Thus, greater *Agility* is achieved.

Sum of indirect effects: Figure 2 shows that *Risk in Supplier* (*SRisk*), perception on *Risk in Demand* (*DRisk*), and *Agility* (*Agil*) are responsible for this indirect relationship, which has sum total of 0.335 illustrates in Table 8. That is, they are the indirect effects among the *Transportation* (*Tran*) and *Customer service* (*CServ*). In two cases, the indirect effect of this relationship is given by only one segment: either *Risk in Demand* (*DRisk*) or *Agility* (*Agil*). However, in the third case, the relationship among *Transportation (Tran)* and *Customer service (CServ)* occurs through two segments: *SRisk* and *Agil*. In the end, value 0.335 is obtained of sum 0.036 and 0.299, corresponding to both indirect effect two and three segments of *Tran* on *CServ* of Table 8. This relationship indicates that when the *Transportation* increases its standard deviation by one unit, the standard deviation of *Customer service* also increases by 0.335 units. This reveals that the appropriate *Transportation* of materials and products is a crucial aspect to reduce *Risk in Demand* and in *Supplier*, and to increase *Customer service* level.

Total effects: Is the result of adding direct and indirect effects. Table 9 presents total effects for the relationships among the variables. For instance, the total effects between the *Logistics services (LServ*) and *Risk in Demand* (D*Risk*) is 0.259; which based on P-value was statistically significant. In other words, availability of *Logistics services* reduces the risk perception and helps achieve timely and complete deliveries of material and make appropriate deliveries to customers. Note that the highest total effect is of the agility occurred on *Customer service* (*CSer*) with 0.581. Similar interpretations can be provided for the remaining relationships in Table 9.

Table 7 Indirect effects to two and three segments between latent variables

Segments	With	Effect indirect of		
		LServ	SRisk	Tran
Two	CServ	0.052(P=0.133)	0.113(P=0.008)	0.299(P<0.001)
	Agil	0.036(P=0.219)		0.063(P=0.090)
Three	CServ	0.021(P=0.291)		0.036(P=0.171)

Table 8 Sum of indirect effects among variables

To	Indirect effects from the variable		
	LServ	SRisk	Tran
CServ	0.073 (P=0.059)	0.113 (P=0.008)	0.335 (P<0.001)
Agil	0.036 (P=0.219)		0.063 (P=0.090)

Table 9 Total effects from latent variables

To	Effects from				
	LServ	SRisk	DRisk	Agil	Tran
CServ	0.073	0.113	0.201	0.581	0.335
SRisk	0.188				0.323
DRisk	0.259				0.272
Agil	0.036	0.194			0.483

3.4 Contributions and industrial relevance

The results from this research confirm suspicions on the existence of direct impacts over dependent latent variables evaluated, and demonstrate that *Logistics services* and *Transportatio*n have effects on the risk perception. Note that we found a new impact from *Risk in Demand* (*DRisk*) on *Customer service* (*CServ*) with a β = 0.20 and a significance level < 0.01. This relationship mean that is important controlling the demand to accomplish with the requirements of customer, this is no doubt because that risks in demand forecasts are due mainly to the lack of connection and coordination among suppliers and manufacturers, and as a result a bad performance at the end of the chain. Results displays in Fig. 2 thus validated seven hypotheses as non-trivial, that is, statistically significant, and one as trivial (H_7), which can help identify strategies to improve *Customer service*, not only considering directly the agility, but other aspects such as risk, *Transportatio*n, and logistic services.

This research argues that to improve the agility in the supply chain in Mexican maquiladoras, it is necessary that transportation performance and risk management be effective. That is, reducing the risk in suppliers and demand by maintaining communication in real time, in addition to lower transportation costs and the satellite connection required to monitor deliveries of material.

This argument is supported by the hypotheses H2 and H6. The first because, there was a direct impact (β = 0.42) towards agility, and the second because, the *Risk in Supplier* presents an impact to *Agility* (β = 0.19). Both impacts explained the 28 % of the variance of the latter showed as R^2 = 0.28. In this sense, major transportation performance increased the agility in manufacturing industries of Ciudad Juarez, the participants sugared that is a key aspect to leads of products to customers.

Also was argument that *the Transportation* decrease the *Risk in Demand,* and *Risk in Suppliers*, which is supported by the hypothesis H1 and H3. Both represent two direct impact with values of β = 0.27 and β = 0.32 respectively , and this mean that in maquiladoras companies of Ciudad Juarez, the participants sugared that the *Transportation* performance in this region is good because is low the risk perception. There is, the communication and the integration of suppliers in manufacturing companies used information technologies to maintained communication and can be adjusted to demand changes or other aspect required.

On the other hand, in this research we also argued that the availability of *Logistics services* affected the perception of risk, both in demand and in suppliers. This implication is supported by hypotheses H4 and

H5, since the results found indicate direct impacts on *Risk in Demand* (β = 0.26) and *Risk in Suppliers* (β = 0.19), where the major impact is about *Risk in Demand*. This means that if *Logistic services* performance is good, i.e. availability of air, land, maritime, financial, legal services and information, the company's operations work best and is perceived less risk as: forecast, visibility, communication and stability. Additionally, there is an association of communication and integration with suppliers and the decrease of the risk perception since errors are diminished, on time deliveries of materials and the number of complete orders is improved. In addition, the findings are important and for instance, the *Risk in Supplier* has influence on agility, and this mean that when there is a major risk in suppliers to complete orders on time, and in exist exacts quantities, it is difficult to achieve agility. Therefore, the managers interested in achieving SC agility should seek opportunities for operational collaboration with their partners. As a relational factor is a driving force of satisfaction and performance for both manufacturers and their suppliers. Regarding hypothesis H_7, the results about this relationship not has important associations to contribute on improving the *Agility*. The improving agility demands the contribution of information, communication, and coordination through information systems, infrastructure, and availability of *Logistics services* and not for the decrease of *Risk in Demand*. The results found to hypothesis H_8 indicating a main contribution of agility on *Customer services*, where the communication and the integration of suppliers with manufacturing companies are critical to make appropriate changes in costumers' needs.

4. Conclusions

Results obtained in this research confirm that in order to assess the competitiveness of companies in terms of customer service, it is important to consider both availability of *Logistics services* and quality of *Transportation* In addition, the impact caused from both elements on *Customer services* occurs through a greater *Agility* and less risk in demand and risks from suppliers, and results show that costumer service is 45 % explained by agility and demand risk perceived. That is, to the higher levels of SC agility, the lower the risk perception and consequently, customer service is improved. Similarly, in order to achieve SC agility, managers must be able to provide logistics services and proper connectivity among SC members through a suitable transportation of materials.

Those findings indicate the importance of proper communication and coordination through information systems and logistics services, which are the starting point for production process. In fact, communication and integration with suppliers is a critical success factor for companies because facilitate operations along the SC, improve delivery time and operational cost. In addition, *Transportation* services and *Logistic services* must be aimed to reduce *Risk in Suppliers* and in *Deman*d, because this lets to increase *Agility* on SC, increasing its performance. Finally, findings indicate that *Customer services* in Ciudad Juarez are adequate in comparison with other regions of Mexico, and in fact, agility has a direct effect of 0.58 on *Customer service*.

Hypotheses here tested were validated using information from Mexican maquiladoras and in future research is planned to compare this industrial sector with others in Mexico and others countries. In addition, the use of information and communication technologies in SC as a latent variable is being considered to be integrated in the structural equation model for knows its role in diminish risk in supplier and in demand, and how it impact the SC integration. Undoubtedly variables assessed in this research are a point of reference to disclose the logistics processes on maquiladoras.

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Solving multi-objective planning model for equipment manufacturing enterprises with dual uncertain demands using NSGA-II algorithm

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ABSTRACT

In the paper we have established a multi-objective planning model. This model can solve the dual uncertainty demand problems of number and delivery time when orders are emergent or are modified for equipment manufacturing enterprises. We used scenario analysis methods to deal with our customers' urgent orders and order revisions. A fuzzy interval analysis was used to describe delivery time requirements, and a random interval analysis was used to describe the quantity of customer demand. The multi-objective production planning model proposed in this paper can solve the objectives pursued by the enterprise to meet the maximization of customer demand and minimization of costs. The NSGA-II genetic algorithm is used to solve the model. Finally, the model is solved by example simulation. Through the input of a large amount of data and the analysis of the operating results, it verified the applicability and effectiveness of the model.

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1. Introduction

With the continuous development of the social economy, the external competition is becoming more and more intensified. Customer requirement is changing, so product demand is becoming more and more individualized, differentiated, diversified and complicated. If the equipment manufacturers want to profit from the fierce market competition, they have to change their single variety and mass production model into a multi variety and small batch production model. The production cycle needs to be shorter and shorter. So it increases the difficulty of the production and operations management of the enterprise. Multi variety products include tangible products, service products, and the combination of tangible product and service product, etc. So the demand is not just a single uncertain demand, but also the cross of more influential and multiple demands. It is mainly manifested in the irregular order quantity of the customer at non-scheduled time and the change of the customer's demand with the passage of time and so on. It mainly includes uncertainty of variety demand, uncertainty of quantity demand, uncertainty of price demand, and uncertainty of delivery time and so on.

There searches on multi variety production plan of traditional equipment manufacturing enterprises are mainly about a specific set of plans. Soysal *et al*. proposed a multi cycle IRP (Inventory Routing Problem) model. It meets the uncertain demand level of service constraints [1].

Hasany and Shafahi mainly developed a two-stage stochastic degree for railway freight blocking problem. The fixed uncertainty of demand and supply resource index is taken into account [2]. Ji *et al*. studied the randomness of the accident and the optimal production plan of a single cycle assembly system under the uncertainty of the capacity of production [3]. Mateo *et al*. studied the production planning model of the fresh vegetable industry, and adopted the two-stage stochastic model to minimize the total purchase cost and to meet the future needs [4]. Masaru and Masahiro tested the supply plan data of a home appliance manufacturer and solved the problem of supply plan optimization under the uncertainty of demand forecast [5]. Ciarallo *et al*. considered the review cycle of uncertain length for the production plan model of a single production disk under random demand and random capacity [6]. Shi *et al*. studied the manufacturer's demand for new products and remanufactured returns for new products. The demand for all products is uncertain and the return is uncertain [7]. Kim *et al*. considered the factors of market demand uncertainty, cost and product characteristics and so on. A mathematical model and iterative algorithm were established to solve the problem of supply structure for manufacturers [8]. Modiano discussed the derivation of the original resource demand function under the uncertain economic environment, and put forward an application to expand the coal power plant to the coal demand and related capacity of the US energy sector [9]. A mathematical model and iterative algorithm were established to solve the problem of supply structure for manufacturers. Based on the stage of credibility theory, in order to minimize the cost of production. Xu *et al*. put forward multi objective decision-making methods [10-11]. Tang *et al*. established non-deterministic polynomial (NP) models [12].

But the above literature does not take into account more uncertainty and event driven production plans. In addition, the equipment manufacturing enterprises do not define the production plan. Not only research content is less, but also all these papers are on the production process of uncertainty in some aspects or in a specific application domain. They lack researches on the uncertainty of demand multiple aspects, and also did not involve more multiple uncertain demand factors.

2. Problem descriptions and hypothesis

2.1 Problem descriptions

In this paper, considering the changes in customer orders requirements and emergency order cases, it produces a series of changes in uncertain demand, including the quantity demand, delivery requirements, and so on. The requirement description of multi variety production planning arrangement in specific equipment manufacturing enterprises is shown in Fig. 1.

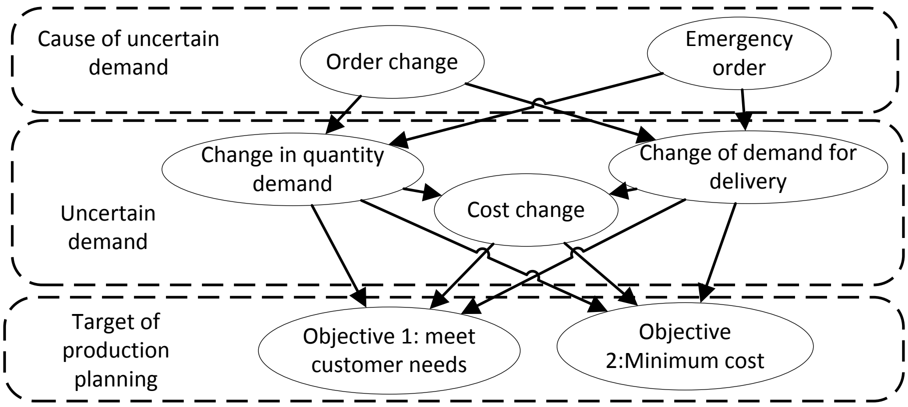

Fig. 1 Uncertain demand of equipment manufacturing enterprise production plans

2.2 Problem hypothesis

According to the requirements of the multiple uncertain requirements mentioned above, the following assumptions are made according to the needs of the model:

- We use the discrete condition of the known probability to describe the uncertainty of the order change or the emergency order of the equipment manufacturing enterprises, and establish the corresponding multi variety production planning model.
- The equipment manufacturing enterprises have the capacity constraints, including the production capacity and the limit of the level of inventory factors.
- The lead time of urgent order or order modification can't be less than the lead time of product production, that is, the product demand time should be greater than the product production plan period, so as to ensure that the demand product can be scheduled for production.

3. Multi-objective planning model for equipment manufacturing enterprises with dual uncertain demands

3.1 Scenario analysis description with dual uncertain demands

The discrete condition of known probability is used in this paper to describe the uncertainty of order change and emergency ordering in equipment manufacturing enterprises, and to establish the corresponding multi product production planning model. There are *n* kinds of products that a production manufacturer can produce, and a total of *m* resources are required.

The multiple product production of equipment manufacturing enterprises can be described with S_1 order change demand scenarios and S_2 emergency order demand scenarios respectively. p_{s1} is the probability of the occurrence of an order change demand scenario $s_1(1, 2, \dots, S_1)$. p_{s2} is the probability of the occurrence of an order change demand scenario $s_2(1, 2, \dots, S_2)$. The combination of S_1 and S_2 constitutes a S scenario. Each scenario represents a group of future equipment manufacturer's multiple production order changes or the forecast of emergency order demand. $\mathrm{p_s}$(That is, p_{s1}, p_{s2}) is the probability of the occurrence of a scenario $s(1, 2, \dots, S)$.

In scenario *s*, we represent the number of requirements for the *t* period by N_t^s. And We represent the market demand for *i* products in the *t* period by N_{it}^s.

<u>*Objective 1:*</u> The enterprise meets the customer's needs as much as possible, that is, the customer demand satisfaction rate is 100 %, that is 1. We represent the pattern as:

$$min \sum_{s=1}^{S} \sum_{t=1}^{T} p_s \cdot \delta N_1^{ts-} + min \sum_{s=1}^{S} \sum_{t=1}^{T} p_s \cdot \delta T_1^{ts-} \tag{1}$$

subject to:

$$\sum_{i=1}^{n} (N_{it}^s - ln_{it}^s) / \sum_{i=1}^{n} N_{it}^s + \delta N_1^{ts-} - \delta N_1^{ts+} = 1, \ \forall t, \ s \tag{2}$$

$$\sum_{i=1}^{n} (TN_{it}^s - lt_{it}^s) / \sum_{i=1}^{n} TN_{it}^s + \delta T_1^{ts-} - \delta T_1^{ts+} = 1, \ \forall t, \ s \tag{3}$$

where:

δN_1^{ts-} is the number of Objective 1 of the *t* period is not reached in situation *s*,

δN_1^{ts+} is the number of Objective 1 of the *t* period is excess in situation *s*,

δT_1^{ts-} is the delivery time of Objective 1 of the *t* period is not reached in situation *s*,

δT_1^{ts+} is the delivery time of Objective 1 of the period is excess in situation *s*.

In addition, the priority level of customer demand and delivery time is different. That is, the expected coefficient of satisfaction is different. The set of alpha α_{Nl}^s and α_{Tl}^s are respectively the expected coefficients of quantity and delivery time of customers *l* under scenario *s*. The target model is modified into is as follows:

$$\alpha_{Nl}^{s} \cdot min \sum_{s=1}^{S} \sum_{t=1}^{T} p_s \cdot \delta N_1^{ts-} + \alpha_{Tl}^{s} \cdot min \sum_{s=1}^{S} \sum_{t=1}^{T} p_s \cdot \delta T_1^{ts-} \tag{4}$$

At the same time, the uncertainty of the quantity of demand and the change of delivery time in the case of emergency order and order modification is considered, setting:

ΔN_{it}: It represents the change in the demand for the *i* product of the *t* cycle.

ΔTN_{it}: It represents the change in the time of customer demand for the enterprise production product *i* in the *t* cycle.

$\widehat{N}_{it}$: It represents the number of needs of the customer's *i* product in the *t* period;

$\widehat{TN}_{it}$: It represents the demand time for the *t* cycle customer to produce the product *i*.

In addition, we define a vector matrix $\gamma = [\gamma_1, \gamma_2]$, among them. Both γ_1 and γ_2 are valued at 0 or 1. It shows whether quantity and delivery time has changed.

Considering the above problems, the Eq. 1 to Eq. 3 is changed to:

$$\alpha_{Nl}^{s} \cdot min \sum_{s=1}^{S} \sum_{t=1}^{T} p_s \cdot \delta N_1^{ts-} + \alpha_{Tl}^{s} \cdot min \sum_{s=1}^{S} \sum_{t=1}^{T} p_s \cdot \delta T_1^{ts-} \tag{5}$$

subject to:

$$\sum_{i=1}^{n} (\widehat{N}_{it}^{s} - ln_{it}^{s}) / \sum_{i=1}^{n} N_{it}^{s} + \delta N_1^{ts-} - \delta N_1^{ts+} = 1, \ \forall t, \ s \tag{6}$$

$$\sum_{i=1}^{n} (\widehat{TN}_{it}^{s} - lt_{it}^{s}) / \sum_{i=1}^{n} TN_{it}^{s} + \delta T_1^{ts-} - \delta T_1^{ts+} = 1, \ \forall t, \ s \tag{7}$$

$$\widehat{N}_{it}^{s} = N_{it} + r_1 \Delta N_{it} \tag{8}$$

$$\widehat{TN}_{it}^{s} = TN_{it} + r_2 \Delta TN_{it} \tag{9}$$

Objective 2: The total production cost of the production plan is minimal. We represent the model as:

$$min\, \delta C_2^{+} \tag{10}$$

Subject to:

$$C/MC + \delta C_2^{-} - \delta C_2^{+} = 1 \tag{11}$$

$$\begin{aligned} \sum_{s=1}^{S} p_s \sum_{t=1}^{T} \Bigg\{ & \sum_{i=1}^{n} (C_{it}^{s} + RC_{it}^{s} + \sum_{j=1}^{m} C_{jt}^{\prime s} \cdot N_{ijt}^{\prime s}) \cdot \widehat{N}_{it}^{s} + \sum_{i=1}^{n} E_{it}^{s} \cdot Max(\widehat{N}_{it}^{s} - G_{it}^{s}, 0) \\ & + \sum_{i=1}^{n} F_{it}^{s} \cdot Max(G_{it}^{s} + N_{it}^{s}, 0) \Bigg\} - C \le 0 \end{aligned} \tag{12}$$

C is the actual cost of production and operation. MC is the minimum cost of production and operation. δC_2^{-} and δC_2^{+} are unreached and excess portion of Objective 2.

Combining the above two objectives, the production planning model of the equipment manufacturing enterprise is set up as follows:

$$MinPP = PP_1\left(\alpha_{Nl}^{s} \cdot min\sum_{s=1}^{S}\sum_{t=1}^{T} p_s \cdot \delta N_1^{ts-} + \alpha_{Tl}^{s} \cdot min\sum_{s=1}^{S}\sum_{t=1}^{T} p_s \cdot \delta T_1^{ts-}\right) + PP_2\delta C_2^{+} \tag{13}$$

PP_1 and PP_2 in the upper formare respectively priority factors in the production plan operation target. In the two goals, the first consideration is as far as possible to meet customer demand. On the basis of the pursuit of cost minimization, so the two priority factor meet the relationship $PP_1 \gg PP_2$. At the same time, the constraint conditions should be satisfied Eq. 2 to Eq. 10. The other constraints are as follows:

Eq. 14 indicates that the number of out of stock of product *i* of period *t* is equal to the quantity of demand subtracting this period of stock. The above described formula is defined as follows:

$$ln_{it} = N_{it} - R_{it}, \; i = 1,2,\ldots,n, \; \forall t, \; s \tag{14}$$

Eq. 15 indicates that the number of shortages of product *i* in period *t* is less than equal to the amount of capacity to produce *i*. The demand for *i* in period *t* is not more than the production capacity of the product *i* in the period *t*.

$$ln_{it} \le W_i, \; i = 1,2,\ldots,n, \; \forall t, \; s \tag{15}$$

Eq. 16 indicates that the number of out of stock of product *i* of period *t* must not be less than the actual demand.

$$ln_{it} \le N_{it}, \; i = 1,2,\ldots,n, \; \forall t, \; s \tag{16}$$

Eq. 17 indicates that the demand for *j* in cycle *t* is not greater than that of the *j* product in the *t* period.

$$\sum_{i=1}^{n} N'_{ijt} - R'_{jt} \le W'_j, \; i = 1,2,\ldots,n, \; j = 1,2,\ldots,m, \; \forall t, \; s \tag{17}$$

Eq. 18 indicates that, in the period *t*, the stock of product *i* equals the final inventory of the product *i* plus the volume of goods for this period. That is to say, it is the demand for the product before the production cycle minus the current stock, that is, the quantity of the products in the life cycle of the product.

$$R_{i\cdot(t+1)} = R_{i\cdot t} + N_{i\cdot(t-T_i)} - R_{i\cdot(t-T_i)}, \; i = 1,2,\ldots,n, \; \forall t, \; s \tag{18}$$

Eq. 19 indicates that the inventory of *i* product in period *t* is less than the maximum inventory of product *i*.

$$R_{it} \le MR_i, \; R_{i\cdot(t+1)} \le MR_i, \; i = 1,2,\ldots,n, \; \forall t, \; s \tag{19}$$

Eq. 20 indicates that production time should not be less than production preparation time plus production time

$$TN_{it} \ge T_{it} + ET_{it}, \; i = 1,2,\ldots,n, \; \forall t, \; s \tag{20}$$

Eq. 21 indicates that Production preparation time is greater than emergency production preparation time.

$$RT_{it} \ge ET_{it}, \; i = 1,2,\ldots,n, \; \forall t, \; s \tag{21}$$

Eq. 22 indicates that the shortage time equals the product production time plus the emergency order time minus the demand time. $lt_{it} > 0$ indicates that product *i* can not be completed according to order requirements in period *t*. and $lt_{it} \le 0$ indicates that product *i* can be complete orders according to order requirements in period *t*.

$$lt_{it} = T_{it} + ET_{it} - TN_{it} \tag{22}$$

Eq. 23 indicates the variables of nonnegative constraints.

$$N_{it}, R_{it}, W_{it}, N'_{ijt}, R'_{jt}, W'_{jt}, P_{it}, C_{it}, C'_{jt}, E_{it}, F_{it}, G_{it} \geq 0, i = 1, 2, \ldots, n, j = 1, 2, \ldots, m, \forall t, s \tag{23}$$

Among them: Eq. 14 to Eq. 17 respectively indicate production out of stock and production capacity balance; Eq. 18 and Eq. 19 respectively constraints on inventory storage capacity; Eq. 20 to Eq. 22 respectively indicate constraints on the lead time of production.

3.2 Quantity demand uncertainty analysis of the random fuzzy description

In the process of actual production operation, equipment manufacturing enterprises in the production process in accordance with the demand of N_{it} orders for production, the amount of demand is not possible to determine the value for sure. In most cases, decision makers often get a value interval of customer demand N_{it} based on order status, market research customers' needs and past data, and mark it with $M_{it} = \left[m_{it}^{min}, m_{it}^{max}\right] = \left\{N_{it} | m_{it}^{min} \leq N_{it} \leq m_{it}^{max}, N_{it} \in R\right\}$. In order to distinguish the common number, the following mark is marked by the number of requirements interval N_{it} as $\widetilde{N}_{it}$. It has no definite distribution function or membership function. If we can give the distribution function or membership function, then the interval variable can be transformed into a random variable or a fuzzy variable.

On the basis of the mathematical model established on the 3.1, the number of the product description demand uncertainty, the constraint Eq. 2 increased uncertainty description. It is expressed as:

$$s.t. \quad \sum_{i=1}^{n} (\widetilde{N}_{it}^{s} - ln_{it}^{s}) / \sum_{i=1}^{n} \widehat{N}_{it}^{s} + \delta N_1^{ts-} - \delta N_1^{ts+} = 1, \forall t, s \tag{24}$$

3.3 Fuzzy analysis description of the uncertainty of delivery demand

The requirements for the lead time of production should be greater than the sum of the emergency order and the time of production. But it is often required to calculate the minimum completion time and the latest completion time as required. And then, it determines the lead time of production. In fact, it is in an area of uncertainty within a certain range. It is expressed as:

$$TD_{it} = \left[td_{it}^{short}, td_{it}^{long}\right] = \left\{TD_{it} | td_{it}^{short} \leq TD_{it} \leq td_{it}^{long}, N_{it} \in R\right\} \tag{25}$$

The satisfactory delivery time for customers is the earliest delivery time period and the latest delivery time period. It is also a time fluctuation range. We record the delivery time of customer demand as follows:

$$TN_{it} = \left[tc_{it}^{earlist}, tc_{it}^{lastest}\right] = \left\{TN_{it} | tc_{it}^{earlist} \leq TN_{it} \leq tc_{it}^{lastest}, N_{it} \in R\right\} \tag{26}$$

So we can know that a constraint relationship between the customer's demand delivery date and the lead time of the enterprise's production is that the delivery time period of the customer demand can't be lower than the completion time of the completion request. That is:

$$td_{it}^{short} \leq tc_{it}^{earlist} \tag{27}$$

Since the customer needs is a time interval, and the customer's delivery time is fuzzy, as long as the requirements of the above Eq. 27 are satisfied. In order to distinguish ordinary numbers, we need to record the customer's delivery time requirement TN_{it} as $\widetilde{TN}_{it}$. It does not have a defined distribution function or membership function. Otherwise, the interval variable can be transformed into a random variable or a fuzzy variable.

According to the mathematical formula in Section 3.1, the uncertainty of the delivery time requirement of the enterprise product is described. For the constraint condition Eq. 3 to increase the uncertainty description, it is expressed as

$$\sum_{i=1}^{n}(\widetilde{TN}_{it}^{s}-lt_{it}^{s})/\sum_{i=1}^{n}\widetilde{TN}_{it}^{s}+\delta T_{1}^{ts-}-\delta T_{1}^{ts+}=1,\ \forall t,\ s \tag{28}$$

To sum up, the production planning model of the equipment manufacturing enterprise with uncertain demand is as follows:

- The objective function: Eq. 13,
- Constraints: Eq. 6, Eq. 7, Eq. 10, Eq. 11, Eq. 12, Eq. 14 to Eq. 24, Eq. 27, and Eq. 28,
- Nonnegative condition: Eq. 23.

The basic symbols and meanings involved in the production planning model of the equipment manufacturing enterprise with multiple uncertain demands are as follows Table 1.

Table 1 The basic symbols and meanings

Variable/ parameter	Meaning
n	The kinds of products that a production manufacturer can produce
m	A total of resources are required
N_{it}	The original planned requirement for the *i* product of the period *t* period
N'_{ijt}	The number of *j* resources needed for the *i* product of the *t* cycle
R_{it}	The inventory of the *i* product of the *t* cycle
R'_{jt}	The inventory of the *j* resource of the *t* cycle
MR_i	The largest inventory of *i* products
MR'_j	The largest inventory of *j* resources
ln_{it}	The number of out of stock of the *i* product of the *t* cycle
lt_{it}	The number of out of stock for production of *i* products in the *t* cycle
C_{it}	The production cost of the *i* product in the t cycle
RC_{it}	The production cost of the production of the *i* product in the *t* cycle
MC_{it}	The minimum cost for the *i* product of the *t* cycle
C'_{jt}	The cost of obtaining the *j* species in the *t* cycle
T_{it}	In the case of meeting the demand, the total production lead time for the production of *i* in the *t* period enterprise
RT_{it}	In the case of meeting the demand, the lead time of production preparation for production *i* in the *t* period enterprise
ET_{it}	In the case of an emergency order, the emergency order lead time of the production of *i* in the *t* period enterprise
TN_{it}	The original planned demand time for the *t* cycle customer to produce the product *i*, that is, the time of delivery
ls_i	The economic volume of the enterprise production product *i*
W_{it}	That the ability of the enterprise to produce product *i* in the t cycle is W_{it} units
MW_{it}	The largest production unit of *i* production in the enterprise's *t* period
W'_{jt}	The ability of the enterprise to produce or obtain resource *j* in the *t* cycle is W'_{jt} units
MW'_{jt}	The largest production unit of the enterprise's *t* cycle production or acquisition of resource *j*
E_{it}	The unit opportunity cost for the production of *i* products in the *t* period
F_{it}	The cost of holding stock in unit *i* product unit in the period *t*
G_{it}	The planned production of the *i* product in the *t* cycle

Among them: i = 1, 2,…,n; j = 1, 2,…,m

4. Used methods

Most of the optimization of production planning belongs to the NP-hard problem, and it is limited by the general precise algorithm. Genetic algorithm is a new global optimization search algorithm, because its principle is simple, and its versatility and robustness is strong, it is especially suitable for parallel processing. Kalyanmoy Deb's elite non dominated sorting genetic algorithm (Nondominated Sorting Genetic Algorithm II) is undoubtedly the most widely applied and the most successful one. The NSGA-II method is adopted in this paper. This method proposes accelerated non dominated sorting algorithm, which reduces the computational complexity of the algorithm from O (mN3) to O (mN2), where m is the number of objective functions and N is population size. The operation process of NSGA-II is drawn as shown in Fig. 2.

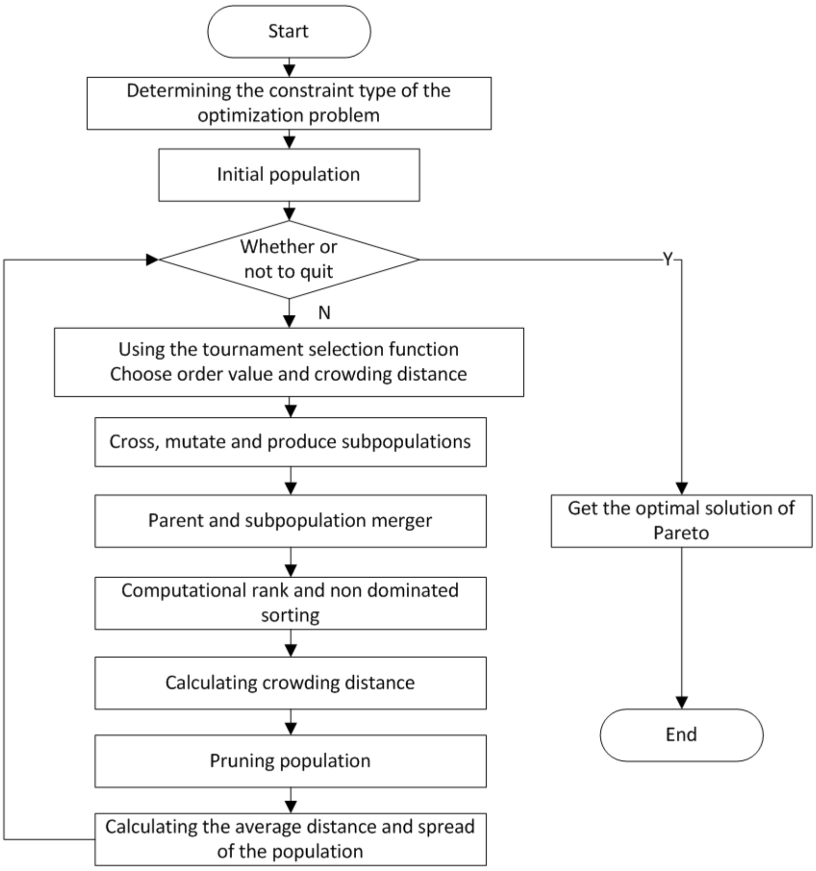

Fig. 2 Diagram: the operation process of NSGA-II

5. Results and discussion

According to the above model in Eq. 13, combined with the simulation example, the multi-objective optimization algorithm NSGA-II is based on the simulation example. The Matlab 2015b version is used to simulate and calculate the results, and the results are analyzed.

5.1 The initial data

Assuming that a production manufacturer can produce a product n = 5, a total of m = 10 resources are needed, and other parameters, as shown in Tables 2 to 11. The probability distribution of order modification and emergency order is 0.4 and 0.6.

Table 2 Product composition table

Name of the product(i) \ Number of resources (j)	$m(1)$	$m(2)$	$m(3)$	$m(4)$	$m(5)$	$m(6)$	$m(7)$	$m(8)$	$m(9)$	$m(10)$
$n(1)$	2	0	4	2	0	3	0	7	0	0
$n(2)$	1	1	0	2	5	0	4	0	0	0
$n(3)$	0	2	3	1	0	2	0	5	0	3
$n(4)$	2	0	4	0	5	0	6	0	9	0
$n(5)$	2	1	0	4	0	2	0	3	0	4

Table 3 Product or resource in t time inventory

Products or resources \ Period	t=1	t=2	t=3	t=4	t=5	Maximum stock
$n(1)$	300	1000	900	400	500	2000
$n(2)$	300	800	900	900	900	2000
$n(3)$	800	600	600	100	900	2000
$n(4)$	900	200	500	800	600	2000
$n(5)$	800	400	1000	900	300	20000
$m(1)$	8000	2000	5000	9000	10000	20000
$m(2)$	7000	10000	6000	1000	2000	20000
$m(3)$	1000	8000	2000	4000	6000	20000
$m(4)$	3000	1000	8000	10000	5000	20000
$m(5)$	2000	10000	5000	1000	5000	20000
$m(6)$	3000	9000	8000	4000	4000	20000
$m(7)$	2000	9000	10000	6000	10000	20000
$m(8)$	1000	9000	5000	4000	2000	20000
$m(9)$	7000	3000	9000	3000	10000	20000
$m(10)$	9000	10000	5000	4000	3000	20000

Table 4 t time product production capacity table

Products \ Period	t=1	t=2	t=3	t=4	t=5
$n(1)$	2000	2000	2000	2000	2000
$n(2)$	2000	2000	2000	2000	2000
$n(3)$	2000	2000	2000	2000	2000
$n(4)$	2000	2000	2000	2000	2000
$n(5)$	2000	2000	2000	2000	2000

Table 5 t = 1 time customer k demand for product production

Products \ Period	k =1	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10	Total
$n(1)$	600	600	800	900	500	100	700	100	500	900	5700
$n(2)$	600	800	400	200	700	900	900	900	300	800	6500
$n(3)$	200	900	200	700	800	1000	100	400	200	300	4800
$n(4)$	800	400	300	1000	100	500	300	200	500	700	4800
$n(5)$	500	500	500	100	1000	500	500	800	200	100	4700

Table 6 t = 1 time requirements for the customer K

Products \ Period	k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10
$n(1)$	12	12	10	15	12	15	12	9	12	14
$n(2)$	10	8	6	10	9	10	9	6	6	11
$n(3)$	14	9	9	14	13	10	10	8	10	10
$n(4)$	14	13	16	10	14	12	11	15	15	16
$n(5)$	6	11	10	9	8	6	9	10	11	5

Table 7 t = 1 time original production plan

Products \ Period	t=1	t=2	t=3	t=4	t=5
$n(1)$	5700	5100	5300	4700	5300
$n(2)$	6500	5700	6500	4400	6000
$n(3)$	4800	4100	6300	6200	6100
$n(4)$	4800	5100	6600	7000	5600
$n(5)$	4700	4500	3600	6400	5900

Table 8 t time resource production or purchasing capacity

Resources \ Period	t=1	t=2	t=3	t=4	t=5
$m(1)$	15000	15000	15000	15000	15000
$m(2)$	15000	15000	15000	15000	15000
$m(3)$	15000	15000	15000	15000	15000
$m(4)$	15000	15000	15000	15000	15000
$m(5)$	15000	15000	15000	15000	15000
$m(6)$	15000	15000	15000	15000	15000
$m(7)$	15000	15000	15000	15000	15000
$m(8)$	15000	15000	15000	15000	15000
$m(9)$	15000	15000	15000	15000	15000
$m(10)$	15000	15000	15000	15000	15000

Table 9 The various costs of resources

Resources \ Cost	Purchasing cost	Unit Holding cost
$m(1)$	2	5
$m(2)$	3	5
$m(3)$	2	5
$m(4)$	1	5
$m(5)$	2	5
$m(6)$	3	5
$m(7)$	4	5
$m(8)$	3	5
$m(9)$	1	5
$m(10)$	2	5

Table 10 t = 1 time lead time of production plan

Products \ Period	Lead time of production	Lead time of prepares	Lead time of emergency order	Total lead time
$n(1)$	7	2	8	11
$n(2)$	5	1	5	8
$n(3)$	6	2	7	10
$n(4)$	8	2	9	12
$n(5)$	4	1	5	7

Table 11 The various costs of products

Products \ Cost	Unit production cost	Production preparation cost	Unit holding cost	Cost of stock loss
$n(1)$	20	10	5	2
$n(2)$	30	15	5	2
$n(3)$	25	12	5	2
$n(4)$	35	14	5	2
$n(5)$	40	12	5	2

5.2 The results

In matlab, the parameters of setting genetic algorithm (NSGA-II) for multi-objective optimization: the objective function is the [1,100] of the random number, production batch PL is 100, the optimal front-end individual coefficient is 0.3, the population size is 500, the largest evolution algebra is 200, the stop algebra is 200, the deviation value of the fitness function is 1e-3. The average distance between individuals and Pareto front of front individual distribution is drawn as shown in Fig. 3.

The average distance between individual shows the average distance between the points of each generation. When the number of variance decreases, the average distance between individuals and the range of fitness value decreased. These graphs reduce the number of variance and reduce the diversity of offspring.

It can be seen from the Pareto front diagram that the Pareto optimal solution of the first front end is distributed evenly. The number of Pareto optimal solutions for the return of the objective function is 150. As for the 150 objective functions 1 and the objective functions 2, and according to the objective function 1, the order of the customer satisfaction is the order. When the value of the target function is the same in objective function 1, the order is then made according to the minimum production cost. And the scatter plot of the target function is drawn as shown in Fig. 4.

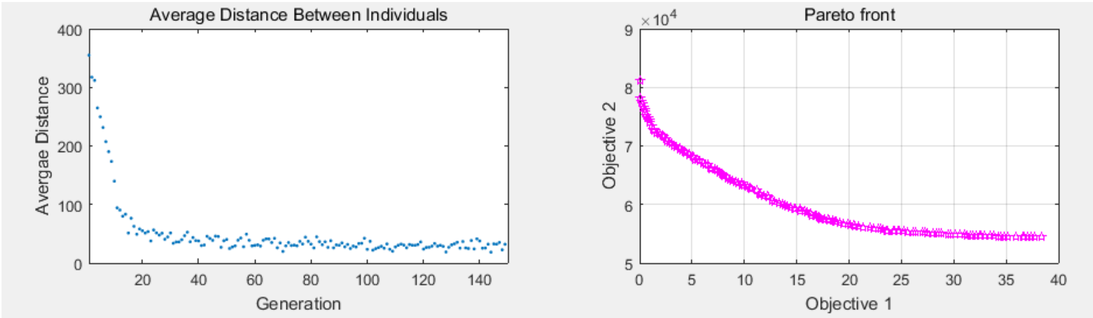

Fig. 3 The average distance between individuals and Pareto front of front individual distribution

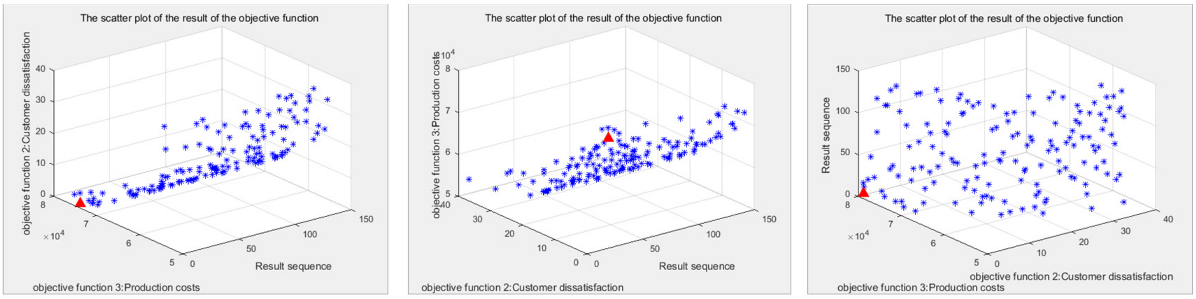

Fig. 4 Three dimensional graph of objective function scatter

From Fig. 3, Fig. 4, and Fig. 5, the program marks the point of the minimum customer dissatisfaction and the production cost center. From all angles of the three-dimensional graph of the scatter plot of the target function, 150 Pareto optimal solutions are obtained by using this model and NSGA-II. These data distribution is concentrated in a plane, which is in line with the requirements of the multi-objective programming. From these 150 sets of data, we find that the nineteenth data is to meet customer needs, that is, the minimum rate of customer order is 0, and the production cost is the smallest and the minimum production cost is 78772.4916553338. Take out the corresponding production schedule as follows Table12 and Table 13.

Table 12 $t = 1$ time product production schedule

Period / Products	k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10
$n(1)$	900	700	800	1000	600	1000	800	600	900	600
$n(2)$	700	800	800	1100	900	500	600	600	700	700
$n(3)$	800	700	600	900	500	600	500	700	800	900
$n(4)$	900	900	400	800	700	600	1000	700	600	500
$n(5)$	900	1100	800	800	1000	700	600	1000	1000	400

Although we chose the most satisfying customer orders, which does not meet the minimum rate and production plan, but the results found in the cost of production may not be minimal, so we can choose the reasonable selection of the optimal solution set, according to the actual needs of enterprises and the enterprise production.

Table 13 Product per cycle production plan

Period / Products	t=1	t=2	t=3	t=4	t=5
$n(1)$	7900	7200	7600	8000	7000
$n(2)$	7400	5800	7900	7700	7500
$n(3)$	7000	7200	7900	7700	6600
$n(4)$	7100	6600	8100	6800	6700
$n(5)$	8300	6700	8900	8100	7600

6. Conclusion

In this paper we analyzed the customer demand issues caused by emergency orders and modified orders for equipment manufacturing enterprises. And we found that multiple uncertainties often existed in the number of customer needs and delivery time. Therefore, we use scenario analysis methods with known probabilities to formulate production plans for equipment manufacturing companies in the event of urgent orders and order modification. Random intervals and fuzzy intervals were used to distinguish between the number of customer requirements and the delivery time requirements. And we established a corresponding multi-product production planning model for equipment manufacturing enterprises. In order to maximize the satisfaction of customer needs and minimization of costs, a multi-objective production planning model was established based on the degree of customer demand for both. This model can achieve the objectives of reducing customer dissatisfaction and minimizing costs and meet the inventory constraints and production constraints of the enterprise's production. In the paper we used NSGA-II algorithm to solve the model. And it is verified that the NSGA-II algorithm can solve the model by means of a simulation example. By means of data input and simulation operations, the results of the operation meet the production needs of the enterprise. It shows that this model can solve the problem of multi-variety production planning for equipment manufacturing enterprises, and it has both operability and feasibility. The establishment of this model is conducive to equipment manufacturers to deal with complex uncertainties and the environment, but also conducive to equipment manufacturers to effectively carry out product production and scheduling.

In the future work, we need to establish more sophisticated models to deal with more rigorous customer demand uncertainties. And the model can deal with more complex production objectives. In addition, the algorithm can be extended to solve problems in multiple ways, such as particle swarm optimization and other multi-objective evolutionary computational algorithms.

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Extended process failure mode and effect analysis (PFMEA) for the automotive industry: The FSQC-PFMEA

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A B S T R A C T

This paper mainly addresses constraints of the PFMEA for the automotive industry. The safety and cost aspect are integrated into traditional severity index. Therefore, for this purpose, three new indices are invented – safety severity index; quality severity index and cost severity index. For both safety severity index and cost severity index, new tables with crisp values belong to the interval (1-10) were invented. While for quality severity index was kept traditional severity table for the automotive industry. The relative importance of these three indices is stated by the fuzzy pair-wise comparison matrix. The weights vectors are calculated by applying the extent analyses. In order to overcome these constraints, but to keep traditional framework of the PFMEA for automotive industry, new fuzzy PFMEA with respect to safety, quality and cost (FSQC-PFMEA) is presented. It can be denotes as the main findings of this paper. At last, the proposed model is tested by real-life data which come from one automotive company supplier and compared with traditional way in the case study. Chosen company use IATF 16949 standard for automotive industry and reference manual presented by Automotive Industry Agency Group (AIAG). Therefore, use of the PFMEA is obligated in this company.

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A R T I C L E I N F O

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1. Introduction

The modern turbulent market puts pressure on companies to respond to customer demands rapidly, with the right quality and at an acceptable price. These three factors (time, quality, and the economic aspect) act in tandem in this case, so the ideal balance between them should be found in order to ensure customer satisfaction [1]. Producing quality is often difficult and time-consuming, with many risks and problems. Such risk or problem during the production process can be the appearance of a defect (failure) [2]. The recommendation of Stamatis [1] is that failure which can disturb the reliable working mode of the production process, should be regulated with source quality, as opposed to prevention rather than detection (or correction). These problems can be controlled with various tools, techniques, and methods. One example of mode frequently used in the automotive industry is the Failure Mode and Effect Analysis – more widely known as FMEA. The focus of this paper is on a production processes in the automotive industry, centering on Process Failure Mode and Effect Analysis (PFMEA).

FMEA has been obligatory since 1993 in the automotive industry by Ford, Chrysler and General Motors. Until now, three standards for the automotive industry have changed, while PFMEA has stayed. First, standard QS 9000 was replaced with ISO/TS 16949 in 2006. Then ISO/TS 16949 was replaced with IATF 16949 in 2016. The framework of PFMEA for the automotive industry is set in reference manual "Potential Failure Mode and Effect Analysis", issued by the Automotive Industry Agency Group (AIAG). The first edition was issued in 1993, the second revision was done in 1998, the third in 2002, and the most current one was published in 2008 [3]. In a review study by Liu *et al*. [4], it was predicted that studies for FMEA will increase in the future, due to the importance of this analysis for the improvement of the reliability of a system. This claim also refers to PFMEA for automotive industry, which was approved with publishing of a new international standard for automotive industry – IATF 16949. In this new international standard, the influence of PFMEA has increased. PFMEA was mentioned in eighteen clauses of the IATF 16949, while in the older standard for automotive industry (ISO/TS 16949), it was mentioned only six times [5, 6].

PFMEA for automotive industry has many advantages, but also many disadvantages. One example of disadvantage is that costs are not factored into decision making during risk prioritization. Only quality and partially safety aspects are included into severity evaluation process. Cost is a very important factor during the risk evaluation phase, especially when it comes to the external costs that can affect a company due to the dissatisfaction of or endangerment of the customer. In a survey research study conducted on 150 quality approved automotive suppliers by Johnson and Khan [7], in 2003, cost was characterized by mean value of importance. Suppliers were more interested in implementing PFMEAs as a requirement for supplier status rather than for internal benefit. These authors suggested the inclusion of costs into the risk prioritization process, as well. Many authors have proposed various approaches to cost inclusion into FMEA analysis. The biggest problem for the automotive industry is that most of these approaches change the structure and framework of the traditional PFMEA. This problem would mostly affect the external auditor. External auditors in the automotive industry are educated according to the traditional PFMEA framework proposed by AIAG. Therefore, modified FMEA approaches should be transformed again into the traditional PFMEA framework as presented in Fig. 1.

One option to maintain the traditional PFMEA framework, but to include costs and safety, is to split risk factors or to include costs into the severity index. These kinds of studies were mentioned as future research in a review study on FMEA conducted by Liu *et al*. [4]. Some authors have already done similar studies. Zammori and Gabbrielli [8] split the severity index into three risk factors: damage, production, and maintenance costs. Another study was conducted by Braglia [9], in which he included expected costs with other indices (severity, occurrence and detection). Both authors used multi-criteria decision making as support for the weighing of risk factors, including the costs. The same problem is identified for safety. Therefore, there is a need for inclusion of safety index into severity evaluation process as well as for costs.

This paper will present the safety, quality and cost model of PFMEA for the automotive industry based on integration of new risk factors (safety and cost) into an already existing model proposed by AIAG. Uncertainties are modeled by using the fuzzy sets theories, in order to keep the traditional PFMEA framework, but to achieve more precise results. A new fuzzy PFMEA model for automotive industry with respect to safety, quality and cost (FSQC-PFMEA), is presented. The FSQC-PFMEA is presented in order to overcome disadvantages of traditional PFMEA for automotive industry, but to keep traditional PFMEA framework.

Fig. 1 Transformation of PFMEA for automotive industry

2. Basic consideration about PFMEA in automotive industry

The main goal of PFMEA is to identify potential or existing failures, evaluate their causes and effects, but also to propose preventive solutions. The ultimate objective is a failure-free product during the production process in order to make it more reliable both product and process. PFMEA is one of two main types of FMEAs in automotive industry. These types are defined according to the current phase where product is located (usually design or process). PFMEA is a living document, which means that it has to be upgraded with new information or changed due to changes in product or production process. For automotive industry, standard PFMEA report (form) is proposed by AIAG [3]. Traditional Risk Priority Number (RPN) is calculated by multiplication of Severity, Occurrence, and Detection (see Eq. 1). These three risk indices and RPN are defined according to the standard tables for automotive industry also proposed by AIAG. RPN range is (1-1000) while risk indices severity, occurrence and detection have range (1-10). Corrective actions should be taken any time, but especially when RPN value exceeds 100 or one of risk indices value exceeds 8. PFMEA is team based analysis. In case of automotive industry is obligated realization of PFMEA with the multidisciplinary team [3, 5].

$$S \times O \times D = RPN \tag{1}$$

Proper use of PFMEA could be of a great importance for automotive industry. There are few research articles which are addressing trends related to PFMEA for automotive industry. Johnson and Khan [7] highlighted some trends for improvement of PFMEA for automotive industry. The most interesting are cost and software solutions with integrated centralized database. There is also trend in integration of lean approach into PFMEA for automotive industry. PFMEA is obligatory by standard in automotive industry and lean is trend in automotive industry [10]. In recent research related to PFMEA for automotive industry, risk priority problems were addressed [11, 12]. These problems were highlighted as one of the most important shortcomings of PFMEA for automotive industry to be addressed [4]. Therefore it could be said that improvements related to RPN are still trend.

3. The proposed FSQC-PFMEA

Respecting to results of a good practice, each business process, but especially a production process has predispositions for occurrence of one or more failures during the time. Generally, identified failures may be presented by the set of indices $I = \{1,..., i,..., I\}$ where I presents the total number identified failures, and the index of each failure is denoted as i, $i = 1,..., I$. It may be comprehended that the realization of each failure i, $i = 1,..., I$ could lead to the occurrence of one or more failure effects which are determined according to evidence data and the results of the best practice.

The failure effects of identified failures have different degrees of seriousness and heaviness. In traditional PFMEA, assessment of severity of failure effect is considered with respects to quality and partially safety. In this paper, a new FSQC-PFMEA, is presented. The modification is performed into: 1) severity index is determined with respect safety severity index, quality severity index and cost severity index, 2) each failure can occur to one or more failure effects under each severity index, 3) these indices have a different relative importance and they are modelled by using the fuzzy set theory [13, 14]. By applying fuzzy sets theory, uncertainties may be described very well. Many authors suggest triangular fuzzy numbers (TFNs) for modelling uncertainties [15, 16]. Handling of uncertainties by TFNs is enough computational simplicity. At the same time, the obtained results are enough exact. Hence, existing uncertainties are modelled by using TFNs.

In this paper, the cost-based scenarios, and safety-based scenarios are developed and incorporated in the overall severity index. The cost-based scenarios are defined according to the relevant literature and expert opinion. For a difference on before mentioned two tables (traditional severity table and cost table) safety scenarios are defined according to the usual scenarios related to hazards and injuries which appear or may appear in industry, and they have to be considered not only for process, but for influence on customer and consumer as well.

3.1 Modelling of the relative importance of safety, quality and cost

It can be assumed that severity influence factors (safety, quality and cost) have a different relative importance. They can be as unchangeable at the level of considered industry under considered time period. Generally, the relative importance of severity indices should be defined at the level of each failure. This paper is related to the automotive industry and only production process it can be assumed that the relative importance of considered severity indices are equal for each failure effects and each failure. Many authors considering that is more precise and more suitable to human decision-making nature to consider each of the severity indices separately during the relative importance estimation between indices. In conventional Analytic Hierarchy Process (AHP) [17], decision makers map estimations to precise numbers. Using the common measurement scale is simple and easy, but it is not sufficient to take into account the uncertainty associated with the mapping of one's perception to a number [18].

Decision makers express their judgments far better by using linguistic terms precise numbers. The number of linguistic expressions is determined by decision makers with respects to kind and size of considered problem. In this paper, are used a three pre-defined linguistic expressions which are modelled by TFNs:

- *Very low importance* (VLW) – (1, 1, 3.5),
- *Low importance* (LW) – (1, 2, 5),
- *Medium importance* (MW) – (1, 3, 5),
- *High importance* (HW) – (1, 4, 5),
- *very high importance* (VHW) – (2, 5, 5).

The domains of these TFNs are defined into the common measurement scale (1-5) [19, 20]. The value 1 i.e. the value 5 denotes that relative importance of severity index k according to severity index $\boldsymbol{k'}$, k, k' = {1,..., K} is the lowest, i.e. the highest, respectively. It should be noted that big matches of defined TFNs implying the decision makers do not have enough data or knowledge and experience about severity index. One of the reasons may be the fact that safety aspect of severity index is not well explained in traditional severity table of PFMEA for the automotive industry.

According to above introduced assumptions, the relative importance of severity indices is stated by the fuzzy pair-wise comparison matrix. It is assumed that decision makers made decision by consensus. The elements of constructed matrix are denoted in Eq. 2. with the lower and upper bounds $l_{kk'}$, $u_{kk'}$ and modal value $m_{kk'}$, respectively.

$$W_{kk'} = (l_{kk'}, m_{kk'} u_{kk'}) \tag{2}$$

If high relative importance of severity index k' holds, then the pair-wise comparison scale can be represented by the TFNs as on Eq. 3.

$$(W_{kk'})^{-1} = \left(\frac{1}{l_{kk'}}, \frac{1}{m_{kk'}}, \frac{1}{u_{kk'}}\right) \tag{3}$$

Decision makers may make errors in judgements. Therefore, it is important to be tested, how many occurred errors influence on estimation accuracy. By the other words to check if mentioned errors are acceptable or not. This decision is based on respecting of the value of consistency coefficient. If the value of consistency coefficient is equal or less than 0.1 it can be assumed that errors assessment is acceptable. Therefore, determining of the weights vectors of severity indices should be based on the stated fuzzy pair-wise comparison matrix.

3.2 Modelling of safety and cost values for PFMEA for the automotive industry

Safety is already defined by crisp values 9 and 10 in severity table for PFMEA for automotive industry, but roughly. In Table 1 are presented 10 different scenarios of safety influence on severity of failure effect. These scenarios are adopted by expert opinion based on the risk scenarios defined in two basic risk estimation practical methods recommended by Macdonald [21]. One of these methods is the "PILZ system" method for risk estimation. This method is useful for a more deterministic mathematical definition of risks, but still contains some scenarios. Another one is suggested by "Guardmaster" (supplier from UK). It could be said that scenarios listed in Table 1 presents a combination and extension of two before mentioned risk estimation methods, adopted to the scale (1-10) in order to satisfy severity estimation principle at traditional PFMEA for automotive industry. As a difference to the quality severity index proposed in AIAGs manual, safety severity index may have more than one scenario. Therefore, these scenarios will be attached to crisp values which belong to the interval (1-10) as it is presented in Table 1.

For definition of cost severity index of failure effects, special table was invented (see Table 2). Table is adopted according to the traditional table for definition of severity index for PFMEA for automotive industry proposed by AIAG. Cost scenarios are defined according to the usual costs appearing in the industry from the production process to the delivery of the products to the customers, but also based on literature review related to costs-based FMEAs [22]. The first five scenarios are determining costs related to the failure occurrence before defective product pass the production process. These costs may be defined as internal costs. Internal costs are cost usually appeared due to: rework, scrap, reproduction, costs of resetting of the production line on previous state for reproduction (like labor, loss of time, material, etc.), etc. Scenarios from 5 to 10 are related to scenario when product/s pass a production process in company and arrive to the customer/consumer. These costs may be defined as external cost. External costs appears due to: warranty, lawsuits, loss of profit, loss of market, loss of customer, etc.

As in case for safety severity index, cost severity index can have more than one scenario as well. Therefore, these scenarios will be attached to real numbers from (1-10) as It is presented in Table 2.

Table 1 Scenario based table for safety severity index

Safety severity index	Scenarios
10	Multiple deaths
9	Death
8	Multiple very heavy persistent consequences/persistent disease
7	Very heavy persistent consequences/persistent disease (disability, etc.)
6	Multiple persistent consequences/persistent disease
5	Persistent consequences/persistent disease (loss of eye, finger, hand, etc.)
4	Bigger fractures/heavier disease (without permanent)
3	Easier fractures/respite disease (without permanent)
2	Cuts/lacerations (first aid)
1	Scratches/contusions (negligible)

Table 2 Scenario based table for cost severity index

Cost severity index	Scenarios
10	Cost from lawsuit due to physical injuries/disability/death of employees, customers or consumers due to failure mode
9	Cost from lawsuit because of delivery of defective (dysfunctional) products/cost from lawsuit because of damage to equipment, products, infrastructure of the customer
8	Costs due to loss of profit if customer does not want to take or buy reproduced products/costs of declining reputation/costs of declining number of clients
7	Warranty costs (reproduction, transport, administration, etc.)
6	Costs of line/production stop of customers production
5	Costs of line/production stop of own production
4	Costs of backup on previous state of production (labor, material, time, equipment availability, etc.)/costs of replacement of defected products with new one/additional costs to suppliers and additional costs of transport
3	Costs of scrap and reproduction
2	Costs of rework
1	No costs/negligible

3.3 The proposed FSQC-PFMEA for automotive industry

RPN definition by using the FSQC-PFMEA is proposed in this paper. The following steps of the proposed model are presented:

Step 1: The fuzzy pair-wise comparison matrix of the relative importance of severity indices is stated as on Eq. 4.

$$[W_{kk'}]_{3x3}, k, k' = 1, \dots, K; k \neq k' \tag{4}$$

Step 2: The fuzzy pair-wise comparison matrix is mapped inti the pair-wise comparison matrix and the coefficient consistency is calculated by using the eigenvalue method.

Step 3: The weights vector is calculated by using extent analysis (see Eq. 5) [23, 24, 25]. Therefore, the elements of weights vector are crisp.

$$[W_k]_{1xK}, k = 1, \dots, K \tag{5}$$

Step 4: The severity indices for failure effect occurring during failure mode *i*, $i = 1,.., I$. S_{ik} should be assigned value of the worst scenarios.

Step 5: Calculate the overall severity index by using (Order Weighted Aggregation) OWA operator [26] (see Eq. 6):

$$S_i = \sum_{k=1}^{K} w_k \times S_{ik} \tag{6}$$

Step 6: Determine value of RPN for failure modes *i*, $i = 1,\dots, I$ (by analogy traditional PFMEA) (see Eq. 7):

$$RPN_i = S_i \times O_i \times D_i \tag{7}$$

Step 7: Failure priorities should be set according to the highest RPN value.

4. Case study: Results and discussion

A case study has to be realized for testing of the FSQC-PFMEA approach. For this purpose, one automotive company has been chosen – a company producing leather upholstery for automobiles. Company is located in the Central Europe region in republic of Serbia. Company is suited by appropriate international standard for automotive industry – IATF 16949. Company uses PFMEA in order to determine risks on failure occurrence and improve reliability of the product during the production process. PFMEA is realized by using reference manual proposed by AIAG.

This case study was conducted according to the flow chart from Fig. 2. A multi-disciplinary team from different sectors was formed first. The fuzzy assessment of the relative importance of the severity indices and their values is performed by the management team. The assessments of decision makers are presented by linguistic expressions in a more precise way, rather than by precise numbers. These linguistic expressions are modelled as triangular fuzzy numbers. Decision makers make decisions by consensus. For realization of this case study, it is very important that team decision makers stay the same for both (traditional and new approach) PFMEA trials, with possibility for inclusion of additional team members if some more information are needed.

Traditional PFMEA for specific product is realized on traditional way. For PFMEA conduction are selected ten failures (see Appendix 1). Seven failures ($i = 1$, $i = 2$, $i = 3$, $i = 4$, $i = 6$, $i = 7$, $i = 8$) are standard failures occurring during production process, while other three failures ($i = 5$, $i = 9$ and $i = 10$) contain a criticality aspect caused by possibility to lead to critical consequences with endangered safety. Respecting to knowledge and results of the best practice for the automotive industry, new safety-based scenarios and cost-based scenarios are proposed. Each scenario is a signed with crisp values. In the same time, the proposed model in this paper enables ranking of failures in automotive company (which gives support in selecting of appropriate management actions). Modification of quality severity index will cause exceeding of the traditional PFMEA framework for automotive industry. Achieved data from PFMEA realization are presented in Appendix 1.

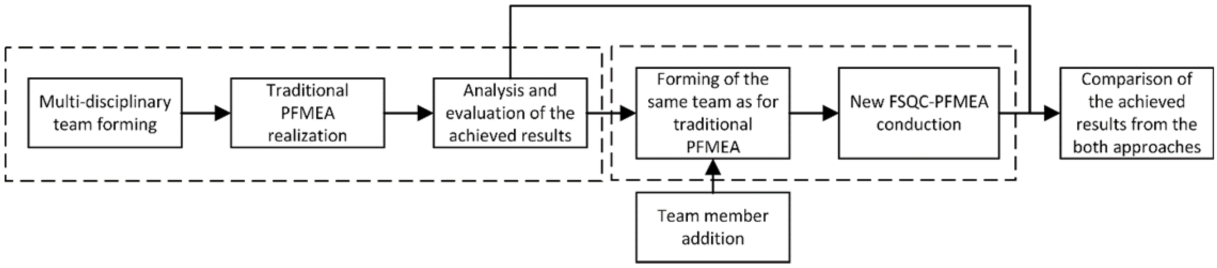

Fig. 2 Flow chart for the case study

Realization of the FSQC-PFMEA method is presented. According to the proposed algorithm (Step 1) the fuzzy pair-wise comparison matrix is constructed (see Eq. 8):

$$\begin{bmatrix} 1 & 1/LW & MW \\ & 1 & HW \\ & & 1 \end{bmatrix} \tag{8}$$

Consistency check for the stated fuzzy matrix and determination of weights vector is given by using the procedure (Step 2 to Step 3 of the proposed algorithm) (see Eq. 9):

$$\begin{bmatrix} 1 & 0.37 & 5 \\ & 1 & 6.67 \\ & & 1 \end{bmatrix} \tag{9}$$

The weights vector is (0.59, 0.3 and 0.11) respectively for (safety severity index, quality severity index and cost severity index). Obtained coefficient consistency is 0.003.

It is assumed that failure mode i, i = 1,…, I leads to the appearance of one or more safety-based scenarios and cost-based scenarios. Determination safety severity index and cost severity index is based on procedure (Step 4 to Step 5 of the proposed algorithm). The proposed procedure is illustrated by example of failure (i = 5). According to opinions of decision makers, failure mode (i = 5) leads to the appearance of from the second of the tenth safety-based scenarios and from sixth to tenth cost-based scenarios denoted.

The overall severity index of failure effect (i = 5) is given by OWA operator (Step 6 of the proposed algorithm) (see Eq. 10):

$$S_5 = 0.34 \times 2 + 0.39 \times 5.95 + 0.27 \times 7.95 = 5.147 \tag{10}$$

Other chosen failures are calculated on similar way as for overall severity index.

RPN for each of the failures i, i = 1,…, I is calculated by applying procedure which is developed in traditional PFMEA (Step 7 of the proposed algorithm). For failure (i = 5), RPN is (see Eq. 11):

$$RPN_5 = 5.147 \times 2 \times 2 = 20.588 \tag{11}$$

It should be noted that quality severity index is determined according to the severity table for automotive industry [9].

The calculated RPN values are sorted in decreasing order (Step 8 of the proposed algorithm). It can be said that the FSQC-PFMEA model is proposed under assumption that O and D have a same weights indices. In practice, this assumption cannot be always introduced.

According to these results the rank of identified failures is determined. At the first place in the rank, there is failure with the highest value of RPN. Similarity, failure with the lowest value of RPN is placed in the last place in the rank. The obtained results by using traditional PFMEA and the FSQC-PFMEA are presented in Table 3.

Obtained results are addressing few differences between Traditional PFMEA for automotive industry and new FSQC-PFMEA. Based on the obtained results, management team may define appropriate activities that should lead to a decrease of risk during the production processes which is further propagated to the long term sustainability.

Table 3 Ranging of the failures on both traditional and FSQC-PFMEA ways of conduction

Failures	RPN obtained by traditional way	Traditional PFMEA rank	RPN obtained by using the FSQC-PFMEA	FSQC-PFMEA rank
i=1	36	7-9	13.44	9
i=2	36	7-9	14.10	8
i=3	108	1	42.30	3
i=4	105	2	39.75	4
i=5	36	7-9	37.64	5
i=6	42	6	15.24	7
i=7	28	10	9.72	10
i=8	54	5	19.17	6
i=9	60	3-4	60.00	1
i=10	60	3-4	58.68	2

The first important difference is in the ranking of failures. With traditional approach failures (i = 1; i = 2 and i = 5) and failures (i = 9 and i = 10) have the same rank, which can be very problematic for decision making. While with new FSQC-PFMEA approach was no matching.

The second thing is that hidden criticality risks noticed at failures (i = 5; i = 9 and i = 10) boosted priority in ranking. The most critical failures (i = 9 and i = 10) moved on the first and second place, while the failure (i = 5) decreased from (7-9th) on 5th place. Therefore, it could be said that new FSQC-PFMEA approach is better to deal with failures with hidden risks.

The third noticed thing is that RPN obtained by new FSQC-PFMEA approach was significantly reduced, compared with traditional approach, it can be a problem for decision makers. Recommendation by AIAG is that failures should be always controlled and reduced, but especially when RPN exceeds value 100 [3]. Users in automotive industry often consider that failure is not critical if some of the S, O and/or D indices exceeds value 8 or RPN value 100, which can be a big problem because of hidden risks. Hidden risks of S, O and D indices are highlighted even in RPN which is given by using the proposed FSQC-PFEMA Therefore, it can be concluded that AIAGs recommendation that risk has to be reduced when RPN exceeds value 100 is not relevant and it just make confusion to users.

5. Conclusion

In this paper is presented a new FSQC-PFMEA for automotive industry which present extension (in the matter of safety and cost) of the PFMEA for automotive industry proposed by AIAG [9].
The main contributions of the proposed model are:

- Two new severity indices (safety and cost) are invented and new correspondingly tables (related to safety and cost) adapted to traditional severity table.
- The weighted overall severity index is calculated in exact manner.

The general limitations related to the FSQC-PFMEA model can be denoted as:

- Fuzzy rating of the relative importance of severity indices depend on knowledge and experience of decision makers.
- Sometimes failure effect does not have safety consequence, but this factor is still taken into consideration during the risk evaluation.
- This model making prioritization of the risks, but it must be counted that all risks must be reduced.
- Quality severity index is based on severity index proposed by AIAG. This table for severity contains two scenarios of safety aspect in severity values 9 and 10. This is not necessary because specialized index for safety severity is invented. But modification of quality severity index will cause exceeding of the traditional PFMEA framework for automotive industry.

This new proposed model FSQC-PFMEA mostly contributes in decision making during the risk selection, but it is very complex and practically hard applicable without some automatized or software solution.

On the whole, this FSQC-PFMEA presents important ground work for quantitative approaches in measurement and ranking of failures in the automotive industry. The further research should include:

- Finding a way to adopt the proposed model in other industries and areas.
- From the traditional PFMEA severity table, safety aspects should be excluded and new quality severity table should be invented.

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Appendix 1

No.	Process	Failure	Failure Effect	Severity (S)	Failure cause	Classification(C)	Occurrence (O)	Current control method	Phase of failure detection	Detection (D)	RPN
1	Measuring of leather thickness	Leather thickness is not according to specification	Final product not in compliance with customer's requirements	6	Supplier factor	HI	2	Measuring with thickness meter	Marking, Cutting, Lamination, Overlock, Separation, Sewing	3	36
2	Cutting of leather	Wrong or incomplete file inserted to the cutting machines	Final product not in compliance with customer's requirements	6	Mistake in program preparation	HI	3	1. Visual control 2. Master sample	Cutting, Lamination, Overlock, Separation, Sewing	2	36
3	Measuring of cut leather parts	Defective parts left cutting process	Final product not in compliance with customer's requirements	6	Sampling frequency is too low	HI	6	Measuring with ruler and comparison with patterns	Cutting, Lamination, Overlock, Separation, Sewing	3	108
4	Cutting of soft materials	Wrong parameter of Orox and Gerber GT cutter	Final product not in compliance with customer's requirements	7	Wrong parameters of machine (speed, vacuum, head speed, number of layers, pressure)	HI	5	Visual control	Cutting, Separation, Sewing	3	105
5	Measuring of AB straps	Defective parts left cutting process	Final product not in compliance with customer's requirements; potential problem with AB deployment	9	/	CC	2	Measurement with ruler and comparison with GO-NOGO jigs	Cutting Separation, Sewing	2	36
6	Perforation of leather cut parts	Wrong angle of perforation	Product not according to drawing specifications	7	Positioning of parts is not according to drawing specifications	HI	3	Visual control	Lamination , Sewing, Quality control	2	42
7	Cutting of profiles	Wrong length/type	Irregular installation	7	Wrong set-up of limiter for cutting profiles	HI	2	1. Measuring tool 2. Visual control	Cutting of profiles, Sewing, Quality control	2	28
8	Cutting of leather part from foam	Damaged part with scissors	Final product not in compliance with customer's requirements	6	Human factor	HI	3	Visual control and comparison with drawings	Lamination, Overlock, Separation, Sewing	3	54
9	Sewing of air bag (AB) straps	Incorrect length of AB strap (if given in technical drawing)	Improper installation of AB	10	Human factor	CC	3	Visual control X-R Chart WI 80.11	1. Sewing phase 2. Quality control	2	60
10	Sewing of AB clips	Wrong position of AB clips (if given in technical drawing)	Improper installation of AB	10	Human factor	CC	3	Visual control SPC QA 80.5	1. Sewing phase 2. Quality control	2	60

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Optimization of a sustainable closed loop supply chain network design under uncertainty using multi-objective evolutionary algorithms

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A B S T R A C T

Environmental, social and economic concerns have highlighted the importance of closed loop supply chain (CLSC) network design problem according to sustainable development. In addition, the uncertainty in decision elements adds to the complexity of this problem. Hence, this paper aims to propose a fuzzy multi-objective mixed integer linear programming (FMOMILP) model for a multi-echelon and multi-period CLSC network that minimize cost and environmental effects and maximize social impacts, simultaneously. At first, the model is converted into a multi-objective mixed-integer linear programming (MOMILP) model by the weighted average method. Due to NP-hardness of the problem, a non-dominated sorting genetic algorithm-II (NSGA-II) is developed to solve this multi-objective mathematical model. The obtained results are validated with the non-dominated ranking genetic algorithm (NRGA), due to there is no benchmark for this problem. In addition, different numerical instances are presented and analyzed with different measures in order to indicate the efficiency of proposed algorithms. The provided results demonstrate that the proposed NSGA-II algorithm is an adequate tool to solve the multi-objective problem of CLSC network design.

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A R T I C L E I N F O

Keywords:
Closed loop supply chain;
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1. Introduction

Recently, the closed loop supply chain (CLSC) increasingly attracted the attention of researchers and practitioners, due to its potential to increase the original equipment manufacturers profit by including the benefit from the collection and recovery of used products. Therefore, designing CLSC networks is of a major importance for organizations. Companies have been continuously pressured by consumers and regulators to control the impact of their products and operations on the environment. Three issues should be considered simultaneously to achieve the sustainable development. These three considerations are economic, environmental, and social aspects. Integration of economic, environmental, and social considerations in sustainable supply chain development, has been receiving an increased attention from companies and academic communities [1]. While the objective of many studies is minimizing the cost or maximizing the profit in supply chain network design (SCND), minimizing the environmental impact and maximizing the social impact are neglected.

The complexity of sustainable SCND is due to the properties of the objectives which are conflicting, inexpressible, sophisticated, and interpenetrating [2]. The uncertainty in decision elements adds to the complexity of the problem. Since there is an inherent uncertainty in the quantity and quality of returned products in reverse chains, considering the uncertainty is a major issue in sustainable SCND problems [3]. The grouping of above-mentioned uncertainties amplifies the total problem uncertainty. The incomplete information and qualitative nature of social and environmental aspects result in the fuzziness of their coefficients in sustainable SCND problems. To obtain an optimum solution for sustainable SCND it is necessary to consider the issue of uncertainty. Researchers implemented several inexact optimization methods to deal with the uncertainties in problems such as interval programming [4], stochastic programming [5], and fuzzy programming [6]. The fuzzy programming approach is more practical among non-deterministic models with multiple objectives. The expansive nature of CLSC networks design as an NP-hard (nondeterministic polynomial time) problem [7, 8]. Achieving reliable and efficient solutions within a practical time becomes more important when dealing with real industrial problems. Meta-heuristic approaches are commonly used for the NP-hard problems. Therefore, multi-objective meta-heuristic approaches are found suitable for solving the problem of sustainable CLSC network design. To ensure the reliability of the solution, the approach should result in Pareto optimal solutions. Since all objectives cannot be optimized by simultaneously, a set of best solutions for different objectives can be developed. In multi-objective evolutionary algorithms (MOEA) [9], such solution set is called Pareto optimal solution that is presented to the expert to make a decision based on the identified criteria.

Based on aforementioned concerns, this paper develops a fuzzy multi-objective mixed integer linear programming (FMOMILP) Model for the problem of CLSC network design in which three objectives of sustainability are met, simultaneously. This method first deals with the uncertainty and applies the weighted average method [10] to convert FMOMILP model into a multi-objective mixed-integer linear programming (MOMILP). The result is a deterministic model. The CLSC network design problem is recognized as an NP-hard problem. In addition, this kind of problems cannot be solved easily by analytical methods and commercial software for large instances. Hence, a non-dominated sorting genetic algorithm (NSGA-II) algorithm is adopted to find the Pareto front sets for the problem of sustainable CLSC network design. This method is used due to its simplicity and efficiency in comparison to analytical methods and other meta-heuristics algorithms. The NSGA-II is currently one of the most popular MOEAs which is used for different multi-objective problems [11]. The complexity of this algorithm is, at most $O(mn^2)$, where m is a number of objectives and n is population size. One of the other advantages of this algorithm is having an explicit diversity preservation mechanism. For the purpose of validating the results, another Non-dominated ranking genetic algorithm (NRGA) is developed and the results are compared. To demonstrate the efficiency of the method, numerical examples are presented. The validation of results is examined utilizing simple additive weighting and T-test methods based on measures of objective function values, spacing index, number of Pareto solutions, and CPU time index.

The major contributions and advantages that distinguish this study from the previous ones are: (1) the proposed approach considers three pillars of sustainability in supply chain network design; (2)the optimization of the forward supply chain and reverse supply chain is conducted simultaneously, while previous studies considered forward chain networks merely; (3) the study considers the uncertainties involved in different levels of supply chain networks to provide a realistic solution; (4) this study largely includes various stages of a CLSC network to imitate a real case; (5) an integrated framework is proposed by using NSGA-II algorithm to develop Pareto-optimal solutions; (6) the provided results of NSGA-II are validated with NRGA based on different instances.

2. Literature review

As it was mentioned, the uncertainty of decision variables increases the complexity of CLSC network design problem. There are several approaches to handling the uncertainty of CLSC network design problem. Stochastic programming is one of the methods used. Zeballos *et al.* [12] developed a two-stage scenario-based modeling for designing and planning decisions in a CLSC network. They considered demand and returns as uncertain parameters. A mixed-integer linear stochastic programming model for a single-period multi-product CLSC location problem including multiple plants, collection centers, and demand markets was introduced by Amin and Zhang [13]. In addition, robust programming is recognized as a commonly used method to design supply chain network under uncertainty. For instance, Hasani *et al*. [14] used an interval robust optimization technique to model a strategic CLSC network design. Ramezani *et al*. [15] presented a multi-objective model to design a forward/reverse supply chain network under an uncertain environment. A robust optimization approach was adopted to address the uncertainty of demand and the return rate with them.

Fuzzy programming was applied to accommodate uncertainty in supply chain network design problem. Vahdani *et al*. [16] proposed a bi-objective interval fuzzy possibilistic chance-constraint mixed integer linear programming to solve the CLSC network design. Sherafati and Bashiri [17] proposed a CLSC network design model considering the suitable transportation modes. They employed fuzzy decision variables in the supply chain network design model. Fuzzy programming has the advantages of being more practical and non-deterministic and it measures the degree of satisfaction of each objective functions. The latter feature helps decision makers to select a preferred efficient solution. Although the uncertainty is addressed in the aforementioned studies, they did not consider the environmental and social impacts in designing the supply chain networks. In addition, the proposed models and solution methods in these studies were applied for small cases. CLSC network design problem is identified as a NP-hard problem, for which and analytical methods and commercial software are not able to provide optimal solutions for large problem situations. Therefore meta-heuristics methods are used to solve such problems. Wang and Hsu [18] developed a revised spanning-tree-based genetic algorithm using determinant encoding representation to optimize a generalized CLSC network design. Pishvaee *et al*. [19] introduced simulated annealing algorithm with special neighborhood search mechanisms to solve a MILP model to design a multistage reverse logistics network. Soleimani *et al*. [20] also employed genetic algorithm to solve a CLSC network design problem. A hybrid meta-heuristic algorithm based on GA and PSO was developed by Soleimani and Kannan [8] to solve large-size instances of CLSC network design problem. Khalilpourazari and Mohammadi [21] proposed a novel meta-heuristic algorithm named water cycle algorithm to solve the mathematical model of CLSC network design. Pasandideh *et al*. [11] applied NASGA-II and NRGA algorithms to solve a multi-product multi-period three-echelon supply-chain-network problem. The analysis of literature review reveals the conducted studies in this field have neglected uncertainty and sustainability issues in the proposed models, simultaneously. While several approaches have been employed to deal with uncertainty in problem of CLSC network design, these studies have not taken sustainability concerns into account and they modeled only one objective function (minimize cost). For this reason, in this paper a FMOMILP model which consider all sustainable development objectives are proposed. In addition, a multi-objective evolutionary algorithm called NSGA-II algorithm is employed to solve this model for large problem instances.

3. Problem formulation

Fig. 1 demonstrates the proposed structure of this study for a multi-echelon, multi-period CLSC network. Four layers in the forward logistics, suppliers, producers, distributors, and customer centers have been taken into account. In addition, in the reverse logistics, there are four layers, collection & inspection, disposal, recycling, and repairing centers. These assumptions and limitations are made in the network configuration: (1) Return rates of products from customer centers, the capacity of all facilities, and product demand are fuzzy parameters; (2) The locations of suppliers and customer centers are fixed and predefined; (3) The potential locations of plants, distributors, collection and inspection, disposal, recycling, and repairing centers are known; (4) The flows are only permitted to be shipped between two consecutive stages in forward and reverse logistics. Furthermore, there are no flows between facilities at the same layer; (5) The transportation cost per product from the supplier to the producers is included in the raw material purchasing cost; (6) The transportation cost of products between all layers remains fixed for all the periods; (7) The inspection cost of the returned products is included in the transportation cost from customer zones to collection & inspection centers; (8) The model is single-product; (9) The model is multi-period.

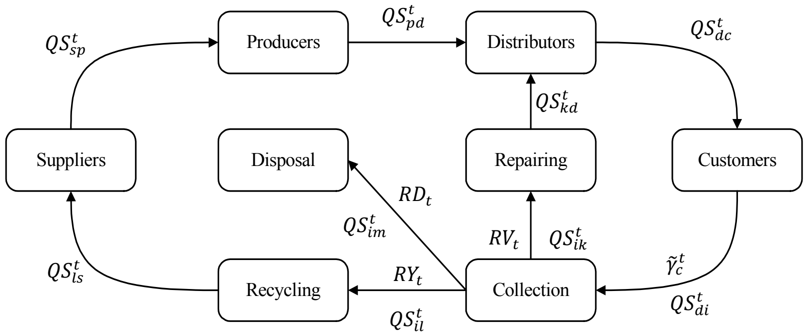

Fig. 1 The network structure of CLSC model

3.1 Objective functions

Three objective functions, minimize cost (Z_1), minimize environmental impacts (Z_2), and maximize social impacts are established for the proposed multi-echelon and multi-period CLSC model. These objective functions are presented by the following equations:

$$\begin{aligned}\text{Min}\\ &= \sum_p\sum_t FC_p\,OP_p^t + \sum_d\sum_t FC_d\,OD_d^t + \sum_i\sum_t FC_i\,OI_i^t + \sum_m\sum_t FC_m\,OM_m^t + \sum_l\sum_t FC_l\,OL_l^t\\ &+ \sum_k\sum_t FC_k\,OK_k^t + \sum_p\sum_d\sum_t MC_p^t\,QS_{pd}^t + \sum_i\sum_l\sum_t RC_l^t\,QS_{il}^t + \sum_k\sum_i\sum_t BC_k^t\,QS_{ik}^t\\ &+ \sum_m\sum_i\sum_t DC_m^t\,QS_{im}^t + \sum_d\sum_p\sum_t TC_{pd}\,QS_{pd}^t + \sum_d\sum_c\sum_t TC_{dc}\,QS_{dc}^t + \sum_c\sum_i\sum_t TC_{ci}\,QS_{ci}^t\\ &+ \sum_i\sum_m\sum_t TC_{im}\,QS_{im}^t + \sum_i\sum_l\sum_t TC_{il}\,QS_{il}^t + \sum_i\sum_k\sum_t TC_{ik}\,QS_{ik}^t + \sum_k\sum_d\sum_t TC_{kd}\,QS_{kd}^t\\ &+ \sum_s\sum_p\sum_t TC_{sp}\,QS_{sp}^t\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Min } EI\\ &= \sum_p\sum_d\sum_t EIP_p\,QS_{pd}^t + \sum_i\sum_m\sum_t EID_m\,QS_{im}^t + \sum_s\sum_p\sum_t EIS_{sp}\,QS_{sp}^t + \sum_p\sum_d\sum_t EIS_{pd}\,QS_{pd}^t\\ &+ \sum_d\sum_c\sum_t EIS_{dc}\,QS_{dc}^t + \sum_c\sum_i\sum_t EIS_{ci}\,QS_{ci}^t\\ &+ \sum_i\sum_m\sum_t EIS_{im}\,QS_{im}^t + \sum_i\sum_l\sum_t EIS_{il}\,QS_{il}^t + \sum_i\sum_k\sum_t EIS_{ik}\,QS_{ik}^t + \sum_l\sum_s\sum_t EIS_{ls}\,QS_{ls}^t\\ &+ \sum_k\sum_d\sum_t EIS_{kd}\,QS_{kd}^t\end{aligned} \tag{2}$$

$$\begin{aligned}\text{Max } SI\\ &= \sum_p\sum_t FJ_p\,OP_p^t + \sum_d\sum_t FJ_d\,OD_d^t + \sum_i\sum_t FJ_i\,OI_i^t + \sum_m\sum_t FJ_m\,OM_m^t + \sum_l\sum_t FJ_l\,OL_l^t\\ &+ \sum_k\sum_t FJ_k\,OK_k^t + \sum_p\sum_d\sum_t VJ_p\,QS_{pd}^t\,/\widetilde{CP}_p^t + \sum_d\sum_c\sum_t VJ_d\,QS_{dc}^t\,/\widetilde{CD}_d^t\\ &+ \sum_c\sum_i\sum_t VJ_i\,QS_{ci}^t\,/\widetilde{CI}_i^t + \sum_i\sum_m\sum_t VJ_m\,QS_{im}^t\,/\widetilde{CM}_m^t + \sum_i\sum_l\sum_t VJ_l\,QS_{il}^t\,/\widetilde{CL}_l^t\\ &+ \sum_i\sum_k\sum_t VJ_k\,QS_{ik}^t\,/\widetilde{CK}_k^t\end{aligned} \tag{3}$$

The first objective function calculates the total cost of the CLSC model. This objective consists of fixed costs of establishing facilities (first six terms), manufacturing, recycling, repairing, and disposal costs (seventh to tenth terms), and transportation costs (eleventh to eighteenth terms). The second function is related to environmental impacts objective function of the CLSC network. The first and second terms are the environmental impacts of producing goods by producers and disposing of returned products by disposal centers. The rest terms in this objective function stand for the environmental impacts of shipping products between facilities. The social impacts of CLSC network design are formulated by the third function. Fixed and variable job opportunities are measures we considered for social impact objective function. In this objective function, the seventh to twelfths terms stand for the created variable jobs.

3.2 Constraints

The following constraints are taking into account:

$$\sum_p QS_{sp}^t \le OS_s^t\, \widetilde{CS}_s^t \qquad \forall\, s,t \tag{4}$$

$$\sum_d QS_{pd}^t \le OP_p^t\, \widetilde{CP}_p^t \qquad \forall\, p,t \tag{5}$$

$$\sum_p QS_{pd}^t + QS_{kd}^t \le OD_d^t\, \widetilde{CD}_d^t \qquad \forall\, d,t \tag{6}$$

$$\sum_c QS_{ci}^t \le OI_i^t\, \widetilde{CI}_i^t \qquad \forall\, i,t \tag{7}$$

$$\sum_i QS_{im}^t \le OM_m^t\, \widetilde{CM}_m^t \qquad \forall\, m,t \tag{8}$$

$$\sum_s QS_{ls}^t \le OL_l^t\, \widetilde{CL}_l^t \qquad \forall\, l,t \tag{9}$$

$$\sum_s QS_{sp}^t = \sum_d QS_{pd}^t \qquad \forall\, p,t \tag{10}$$

$$\sum_k QS_{kd}^t + \sum_p QS_{pd}^t = \sum_c QS_{dc}^t \qquad \forall\, d,t \tag{11}$$

$$\sum_c QS_{ci}^t = \sum_m QS_{im}^t + \sum_l QS_{il}^t + \sum_k QS_{ik}^t \qquad \forall\, i,t \tag{12}$$

$$\sum_l QS_{il}^t = \sum_c QS_{ci}^t\, RY_t \qquad \forall\, i,t \tag{13}$$

$$\sum_i QS_{il}^t = \sum_s QS_{ls}^t \qquad \forall\, l,t \tag{14}$$

$$\sum_k QS_{ik}^t = \sum_c QS_{ci}^t\, RV_t \qquad \forall\, i,t \tag{15}$$

$$\sum_i QS_{ik}^t = \sum_d QS_{kd}^t \qquad \forall\, k,t \tag{16}$$

$$\sum_m QS_{im}^t = \sum_c QS_{ci}^t\, RD_t \qquad \forall\, i,t \tag{17}$$

$$\sum_d QS_{dc}^t = \widetilde{DE}_c^t \qquad \forall\, c,t \tag{18}$$

$$\sum_i QS_{ci}^t = \widetilde{DE}_c^t * \tilde{\gamma}_c^t \qquad \forall\, c,t \tag{19}$$

$$\sum_s OS_s^t \le S \qquad \forall\, t \tag{20}$$

$$\sum_p OP_p^t \le P \qquad \forall\, t \tag{21}$$

$$\sum_d OD_d^t \le D \qquad \forall\, t \tag{22}$$

$$\sum_i OI_i^t \le I \qquad \forall\, t \tag{23}$$

$$\sum_m OM_m^t \le M \qquad \forall\, t \tag{24}$$

$$\sum_l OL_l^t \le L \qquad \forall\, t \tag{25}$$

$$\sum_k OK_k^t \le K \qquad \forall\, t \tag{26}$$

$$QS_{sp}^t, QS_{pd}^t, QS_{dc}^t, QS_{ci}^t, QS_{im}^t, QS_{il}^t, QS_{ik}^t, QS_{ls}^t, QS_{kd}^t \ge 0 \qquad \forall i,j,k,l,m,p,t,c,d \tag{27}$$

$$OS_s^t, OP_p^t, OD_d^t, OI_i^t, OM_m^t, OL_l^t, OK_k^t \in \{0,1\} \qquad \forall i,k,l,m,p,s,t,d \tag{28}$$

Constraints Eqs. 4 to 9 are capacity constraints. Constraints Eqs. 4, 5, 9 control output capacity of suppliers, producers, and recycling centers in each period respectively. Constraints Eqs. 6 to 8 control input capacity of distributors, collection and inspection centers, and disposal centers in each period respectively. Constraints Eqs. 10 to 17 are balance constraints which guarantee the flow entering to utilities are equal to sum of the flow existing from utilities. Constraints Eqs. 10 to 12 are balance constraints of producers, distributors, and collection & inspection centers respectively. Constraints Eqs. 13 and 14 are balance constraints of recycling centers. Constraints Eqs. 15 and 16 are balance constraints of repairing centers. Constraint Eq. 17 is balance constraint of disposal centers. Constraint Eq. 18 ensures that all customer demands should be met in customer centers. Constraint Eq. 19 shows the amount of returned products which are collected from customer centers. Constraints Eqs. 19 to 26 limit the maximum number of allowable locations. Constraints Eqs. 27 and 28 represent the non-negativity and integrality of variables.

4. Auxiliary MOMILP

As seen from the proposed model for CLSC network design in section 3, fuzzy parameters are employed in objective functions and constraints. For this reason, to solve this model, it should be firstly changed to deterministic model. Hence, the weighted average method [10] is implemented to convert the proposed FMOMILP model into an equivalent auxiliary crisp multiple objective mixed integer linear programming (MOMILP) model. This process is done by the following steps:

Step 1: Strategy for fuzzy objectives

Finding an ideal solution is not guaranteed for the proposed model due to used fuzzy coefficients for the objective function of Social Impacts (*SI*) (Eq. 3). Several approaches are proposed to obtain compromise solutions when there are fuzzy objective functions [10]. The proposed approach by Lai and Hwang [10] has less restrictive assumptions in comparison with other methods and practically is easy in order to use. Hence, the approach of Lai and Hwang is employed to deal with fuzzy objective functions in this study. For this aim, an auxiliary MOMILP model is provided with three objective functions to convert the fuzzy objective function of *SI* to precise one. The triangular possibility distributions are taken into account for fuzzy parameters of this objective function. Based on the proposed approach by Lai and Hwang [10], the fuzzy objective function, maximize *SI*, is converted into minimize (${SI_s}^m$-${SI_s}^p$) (Z_3), maximize ${SI_s}^m$ (Z_4), and maximize (${SI_s}^o$-${SI_s}^m$) (Z_5). The new crisp objective functions are modeled by following equations:

$$\begin{aligned}
&\text{Min } (SI^m - SI^p) = Z_3 \\
&= \sum_p \sum_t FJ_p\, OP_p^t + \sum_d \sum_t FJ_d\, OD_d^t + \sum_i \sum_t FJ_i\, OI_i^t + \sum_m \sum_t FJ_m\, OM_m^t + \sum_l \sum_t FJ_l\, OL_l^t \\
&+ \sum_k \sum_t FJ_k\, OK_k^t + \sum_p \sum_d \sum_t VJ_p\, QS_{pd}^t /(CP_p^{t,m} - CP_p^{t,p}) + \sum_d \sum_c \sum_t VJ_d\, QS_{dc}^t /(CD_d^{t,m} - CD_d^{t,p}) \\
&+ \sum_c \sum_i \sum_t VJ_i\, QS_{ci}^t /(CI_i^{t,m} - CI_i^{t,p}) + \sum_i \sum_m \sum_t VJ_m\, QS_{im}^t /(CM_m^{t,m} - CM_m^{t,p}) \\
&+ \sum_i \sum_l \sum_t VJ_l\, QS_{il}^t /(CL_l^{t,m} - CL_l^{t,p}) + \sum_i \sum_k \sum_t VJ_k\, QS_{ik}^t /(CK_k^{t,m} - CK_k^{t,p})
\end{aligned} \tag{29}$$

$$\begin{aligned}
&\text{Max } SI^m = Z_4 \\
&= \sum_p \sum_t FJ_p\, OP_p^t + \sum_d \sum_t FJ_d\, OD_d^t + \sum_i \sum_t FJ_i\, OI_i^t + \sum_m \sum_t FJ_m\, OM_m^t + \sum_l \sum_t FJ_l\, OL_l^t \\
&+ \sum_k \sum_t FJ_k\, OK_k^t + \sum_p \sum_d \sum_t VJ_p\, QS_{pd}^t /CP_p^{t,m} + \sum_d \sum_c \sum_t VJ_d\, QS_{dc}^t /CP_d^{t,m} \\
&+ \sum_c \sum_i \sum_t VJ_i\, QS_{ci}^t /CI_i^{t,m} + \sum_i \sum_m \sum_t VJ_m\, QS_{im}^t /CM_m^{t,m} + \sum_i \sum_l \sum_t VJ_l\, QS_{il}^t /CL_l^{t,m} \\
&+ \sum_i \sum_k \sum_t VJ_k\, QS_{ik}^t /CK_k^{t,m}
\end{aligned} \tag{30}$$

$$\begin{aligned}
&\text{Max}\,(SI^{o} - SI^{m}) = Z_5 \\
&= \sum_{p}\sum_{t} FJ_p\, OP_p^t + \sum_{d}\sum_{t} FJ_d\, OD_d^t + \sum_{i}\sum_{t} FJ_i\, OI_i^t + \sum_{m}\sum_{t} FJ_m\, OM_m^t + \sum_{l}\sum_{t} FJ_l\, OL_l^t \\
&+ \sum_{k}\sum_{t} FJ_k\, OK_k^t + \sum_{p}\sum_{d}\sum_{t} VJ_p\, QS_{pd}^t /(CP_p^{t,o} - CP_p^{t,m}) + \sum_{d}\sum_{c}\sum_{t} VJ_d\, QS_{dc}^t /(CD_d^{t,o} - CD_d^{t,m}) \\
&+ \sum_{c}\sum_{i}\sum_{t} VJ_i\, QS_{ci}^t /(CI_i^{t,o} - CI_i^{t,m}) + \sum_{i}\sum_{m}\sum_{t} VJ_m\, QS_{im}^t /(CI_m^{t,o} - CI_m^{t,m}) \\
&+ \sum_{i}\sum_{l}\sum_{t} VJ_l\, QS_{il}^t /(CI_l^{t,o} - CI_l^{t,m}) + \sum_{i}\sum_{k}\sum_{t} VJ_k\, QS_{ik}^t /(CK_k^{t,o} - CK_k^{t,m})
\end{aligned} \tag{31}$$

Step 2: Strategy for fuzzy constraints

In this study, the pattern of triangular distribution is implemented to demonstrate all of the fuzzy numbers in constraints. The simplicity and flexibility of the fuzzy arithmetic operations are the main reason to employ triangular fuzzy numbers in this study [10]. Triangular patterns provide decision makers to define fuzzy numbers in three prominent data points: the most pessimistic value and the optimistic value with possibility degree of 0, and the most likely value with possibility degree of 1. The triangular fuzzy numbers membership functions as linear, which makes it computationally efficient by having a simple formulation in comparing to nonlinear distributions constructions.

A triangular distribution of $\widetilde{CS}_s^t$ consists of: (1) the most pessimistic value ($CS_s^{t,p}$) – it has a very low probability (possibility degree 0) of belonging to the set of accessible values; (2) the most possible value ($CS_s^{t,m}$) – it has a very high probability (possibility degree 1) of belongings to the set of accessible values; (3) the most optimistic value ($CS_s^{t,o}$) – it has a very low probability (possibility degree 0) of belonging to the set of available values [22]. Recalling constraint Eq. 4 from the original FMOMILP model formulated in Section 3 considers situations in which supplier capacity, $\widetilde{CS}_s^t$, is a triangular fuzzy number with most and least likely values. In this study, the weighted average method is applied to convert fuzzy numbers (such as $\widetilde{CS}_s^t$) into a crisp number. Taking considerations β as the minimum acceptable membership level, the corresponding auxiliary crisp inequality of constraint Eq. 4 can be represented as follows:

$$\sum_{p} QS_{sp}^t \leq OS_s^t\,(W_1 CS_{s,\beta}^{t,p} + W_2 CS_{s,\beta}^{t,m} + W_3 CS_{s,\beta}^{t,o}) \qquad \forall\, s,t \tag{32}$$

Similarly, the corresponding auxiliary crisp inequalities of constraints Eqs. 5 to 9 and Eqs. 18 to 19 are obtained regarding β as the minimum acceptable membership level.

5. Used methods

Two approaches can be followed solving complicated multi-objective optimization problems using evolutionary algorithms two approaches. In the first approach, a multi-objective problem is turned into a single-objective problem. The second approach first creates multiple best (Pareto optimal) solutions for each objective and then finds the best solution among them. The first approach, uses some multi-criteria decision making algorithm to transfer the problem into a single objective one [23]. Methods such as GA, simulated annealing (SA), imperialist competition algorithm (ICA), harmony search algorithm (HAS), and particle swarm optimization (PSO) can be used in this stage [24]. In the second approach multi-objective evolutionary algorithms (MOEA), such as non-dominated sorting genetic algorithm (NSGA-II), non-dominated ranking genetic algorithm (NRGA), and multi-objective particle swarm optimization (MOPSO), can be used to arrive at the solution set [25]. MOEAs are preferred over SOEAs due to the speed of simulation; single simulation run is required to reach a solution. Diversity and convergence distinguish the MOEAs from single-objective optimization algorithms. Diversity maintains the variety within the Pareto-optimal set solutions, while convergence aims at directing the solutions to the optimal Pareto set [24]. In this section, a multi-objective evolutionary algorithm (MOEA) is presented, among the MOEAs, the non-dominated sorting genetic algorithm (NSGA-II) is preferred. NSGA-II is commonly used for similar problems. To validate the results, since no benchmark algorithms are available, this study applies a different GA based algorithm called non-dominated ranking genetic algorithm (NRGA).

5.1. NSGA II

The NSGA II developed by Deb *et al*. [24], is an extension of the non-dominated sorting genetic algorithm (NSGA), [26, 27], in which an extra sorting criterion was introduced. Both algorithms are developed to deal with multi-objective optimization problems and both use Goldberg's non-domination criterion to rank the solutions. NSGA uses a fitness sharing parameter to control the diversity of solutions and is found to be highly sensitive to this parameter. Therefore in NSGA II the crowding distance parameter which is a second-order sorting criterion is used that improves the efficiency of this method. The detailed description of NSGA-II is as follow. First, it generates a mating pool with binary tournament selection. Second, all the members go through a mutation and crossover processes. Third, a larger population is generated by merging the old solutions with the newly generated solutions. Forth, the population is sorted based on the members' rank and crowding distances. Finally, selected members that are sorted higher are kept and the rest are deleted. The previous steps are repeated until the stopping condition is met. The final non-dominated members create the Pareto frontier set for the multi-objective optimization problem.

5.2. NRGA

The non-dominated ranking genetic algorithm (NRGA) is a commonly used MOEA algorithm that is developed to deal with multi-objective optimization problems with creating a Pareto front optimal set. NRGA mechanism is similar to NSGA-II except for the step in which the older members merge with the new generation in the mating pool. The selection process of old members is developed in NRGA to integrate the Pareto based population-ranking algorithm with ranked-based roulette wheel (RBRW) selection process [28].

5.3. Generic operators for GA-based algorithms

Chromosome representation

In a genetic algorithm, a chromosome consist of a series of genes that are arranged sequentially where genes represent decision variables. In this paper, the matrix format is employed to represent the chromosome. Based on the proposed CLSC network structure, nine connections are defined to connect the utilities in this network. To produce each chromosome nine linear programming problems are solved. For instance, a network with 3 suppliers and 4 producers, is defined by a 3×4 dimension matrix. Fig. 2 displays a graphical representation of the chromosome.

	P_1	P_2	P_3	P_4
S_1	200	200	150	100
S_2	300	150	200	100
S_3	200	100	150	200

Fig. 2 Chromosome representation

Selection strategy

The selection strategy in NSGA-II uses fast non-dominated sorting, density estimation, and crowded comparison operators [24]. To classify the members in non- domination levels the fast non-dominated sorting operator is used. To find the density of solutions around a specific member in the population, the density estimation operator is used. And finally, to ensure that members are selected from a uniform Pareto front the crowded comparison operator is applied [24]. The binary tournament selection strategy is applied based on the described operators to find the solutions. In this process, the rank and crowding distance of each member is considered for the selection.

Crossover

Crossover operations in NSGA-II ensure that the new population is created by inheriting the good genes from the parents for the purpose of improving the chromosome. Commonly used crossover operators are single-point, two-point, and multiple-point operators. However there are other methods for cross over operation such as partially mapped crossover (PMX), ordered crossover (OX), cycle crossover (CX), and arithmetic crossover. In this research, the arithmetic crossover operator is used. This method combines the parent chromosomes linearly to create the new generation using Eqs. 33 and 34 [27].

$$\text{Offspring 1} = \alpha \times \text{parent 1} + (1-\alpha) \times \text{parent 2} \tag{33}$$

$$\text{Offspring 2} = (1-\alpha) \times \text{parent 1} + \alpha \times \text{parent 2} \tag{34}$$

where $0 < \alpha < 1$. The chance of crossing the parents is indicated by P_c and it is considered high for values above 80 %.

Mutation

Mutation happens after the crossover operation in NSGA-II. The purpose of this step is to create diversity in the newly generated populations. Therefore, moving from the parent generation to the new generation, the mutation operator searches the new solution space for including the solutions. This operator selects a chromosome and randomly chooses some genes and changes their values. The probability of this change is the mutation probability, P_m. There are several mutation operators, such as scramble mutation, random resetting mutation, and inversion mutation.

6. Results and discussion

For the purpose of verifying the proposed meta-heuristic algorithms in this study, experiments with different properties are designed. Nine designed experiments are different in size and are categorized as small, medium, and large size problems. The parameters in each problem are set by randomly assigning values from a uniform distribution with lower and upper limits. Tables 1 and 2 present the experiments and their assigned properties.

Table 1 Generated experiments

	S	P	D	C	I	K	L	M	T
	3	2	3	4	3	2	2	2	6
Small	4	2	2	5	2	2	2	2	6
	2	3	3	4	3	2	3	3	6
	8	8	5	10	7	5	5	5	6
Medium	7	9	6	8	5	6	6	6	6
	9	8	8	8	6	6	5	5	6
	15	15	10	20	10	8	8	8	6
Large	20	15	15	25	10	8	8	10	6
	15	20	10	20	8	10	10	8	6

Table 2 The sources of random parameters of CLSC

Parameter	Range	Parameter	Range
$\widetilde{CS}_s^t, \widetilde{CP}_p^t, \widetilde{CD}_d^t, \widetilde{CI}_i^t, \widetilde{CM}_m^t, \widetilde{CL}_l^t, \widetilde{CK}_k^t$	[2,000 , 4,000]	$FC_d, FC_i, FC_m, FC_l, FC_k$	[30,000 , 60,000]
$TC_{pd}, TC_{dc}, TC_{ci}, TC_{im}, TC_{il}, TC_{ik}, TC_{ls}, TC_{kd}$	[3, 10]	$EIS_{sp}, EIS_{pd}, EIS_{dc}, EIS_{ci}, EIS_{im}, EIS_{il}, EIS_{ik}, EIS_{ls}, EIS_{kd}, EID_m, EIP_p$	[10, 30]
TC_{sp}	[30, 50]	MC_p^t	[150, 200]
$FJ_p, FJ_d, FJ_i, FJ_m, FJ_l, FJ_k$	[5, 10]	DC_m^t, RC_l^t, BC_k^t	[20, 40]
$VJ_p, VJ_d, VJ_i, VJ_m, VJ_l, VJ_k$	[0.4 , 0.6]	$\widetilde{DE}_c^t$	[400, 700]
$\tilde{\gamma}_c^t$	[0.5 , 0.8]		

In addition, for the proposed meta-heuristic algorithms a set of parameters are taken into account; the population number is 100, the generation number is 200, the crossover probability is 0.9, the mutation probability is 0.05. These parameters are chosen empirically based on a trial and error method. All computational work was accomplished on a personal computer (32-bit operating system, 2.53 GHz CPU, and 4.00 GB).

There are various metrics to assess the performance of MOEAs. This study applies three commonly used metrics for this purpose:

Spacing Index

This index takes the non-dominated vectors and calculates the variance of the distance of neighboring solutions [27].

$$SI = \sum_{i=1}^{|n|} \frac{|d_i - \bar{d}|}{|n|} \tag{35}$$

with, $d_i = min \sqrt{\sum_{m=1}^{5}(f_m^i - f_m^k)}$ and $\bar{d} = \sum_{i=1}^{n} \frac{d_i}{|n|}$, where $\bar{d}$ indicates all averages of distances and n indicates the Pareto set solutions, f represents the objective function values. Accordingly, $|n|$ represents the cardinality of n, and the number of objectives is presented by m.

Number of Pareto Solution (NPI) Index

The *NPI* index measures how many Pareto solutions are found by each algorithm.

CPUTI (CPU Time Index)

Measuring the speed of an algorithm with this index is in terms of CPU time needed to find the Pareto-optimal solution.

The NSGA-II and NRGA algorithms are compared based on Z_1, Z_2, Z_3, Z_4, Z_5, *SI*, *NPI*, and *CPUTI* indexes. In every run, the algorithm finds a set of Pareto-optimal solutions. The objective functions are compared by taking the minimum values for Z_1, Z_2, and Z_3, and the maximum values for Z_4, Z_5. Table 3 presents the results of the 9 experiments by NSGA-II and NRGA.

Table 3 The NSGA II and NRGA results

		Z_1	Z_2	Z_3	Z_4	Z_5	*SI*	*NPI*	*CPUTI*
NSGA-II	Small	24,611,010	1,575,001	469	449	453	72	8	207
		25,192,232	1,513,117	497	471	469	96	12	205
		24,817,245	1,561,114	475	445	455	536	7	209
	Medium	73,934,328	4,027,728	1,185	1,109	1,173	409	5	267
		71,819,429	4,011,342	1,019	1,022	1,135	382	13	270
		71,127,814	4,203,279	1,195	1,127	1,163	331	10	275
	Large	152,596,807	8,813,690	2,213	2,077	2,193	2,032	7	327
		175,133,714	8,019,370	2,291	2,113	2,348	1,467	6	320
		178,715,402	8,113,098	2,301	2,193	2,285	487	11	344
NRGA	Small	24,856,211	1,517,229	477	475	451	315	5	331
		24,975,107	1,575,348	491	460	452	319	27	278
		25,134,429	1,631,459	475	452	451	471	3	261
	Medium	74,257,191	4,301,475	1,282	1,187	1,159	212	7	315
		72,517,734	4,157,209	1,122	1,016	1,105	330	5	291
		71,039,875	4,076,342	1,031	1,173	1,183	112	5	297
	Large	155,375,108	7,955,179	2,347	1,952	2,017	767	3	512
		175,917,335	8,245,341	2,375	2,025	2,015	2,027	12	447
		177,009,375	8,279,351	2,410	2,001	2,255	1,103	10	420

Table 4 The p-values of the t-tests on the equality of performance measures

	Z_1	Z_2	Z_3	Z_4	Z_5	*SI*	*NPI*	*CPUTI*
P-value	0.398	0.926	0.227	0.343	0.129	0.928	0.927	0.002

The T-test is selected to examine the hypothesis as a common approach to test the equality of two populations based on parameters. The considered hypothesis for this test is, there is no significant difference between the results obtained by NSGA-II and NRGA for the same experiments. The t-test result does not reject the hypothesis and shows that there is no significant difference between the two test results (Table 4). The P-value is found to be beyond the condition of this test which requires the significance level of α = 0.05. Therefore, the NSGA-II results are considered to be validated by comparing to those of NRGA.

The validation of results is further examined using the simple additive weighting (SAW) introduced by Hwang and Yoon [23] is an MADM method that is used for this purpose. The SAW as a second method can help to determine which of the NSGA-II or NRGA have a better result. Table 5 illustrates the SAW evaluation of these algorithms which suggests the superiority of NSGA-II for all problem indices. However, the results from NRGA are satisfactory. Therefore it can be concluded that while both NSGA-II and NRGA provide valid and satisfactory results for SCN problem, the NSGA-II is superior compared to NRGA.

Table 5 The results of SAW method

Small			Medium			Large		
NSGA-II	NRGA	Prefer	NSGA-II	NRGA	Prefer	NSGA-II	NRGA	Prefer
0.9885	0.8059	NSGA-II	0.8958	0.9615	NRGA	0.9100	0.8564	NSGA-II
0.9279	0.8674	NSGA-II	0.9829	0.8929	NSGA-II	0.9375	0.8986	NSGA-II
0.9829	0.8956	NSGA-II	0.8891	0.9282	NRGA	0.9988	0.8754	NSGA-II

7. Conclusion

In this study, an FMOMILP model for a CLSC network design problem was developed. Three objective functions of sustainability that minimize costs and environmental impacts and maximize social impacts, were considered simultaneously. The FMOMILP model was converted into a deterministic MOMILP model by using the weighted average method. As the model developed in this study was hard to be solved analytically, a multi-objective genetic algorithm based on NSGA-II algorithm was developed to find Pareto fronts. Since there was no benchmark for this problem, the obtained results were validated with NRGA. Nine random examples with different sizes of small, medium, and large were provided to demonstrate the efficiency of the proposed algorithms. In addition, these eight performance measures (Z_1, Z_2, Z_3, Z_4, Z_5, SI, NPI, and $CPUTI$) were employed to compare the performance of these algorithms. Two-sample tests were implemented to compare the differences between the eight performance measures for these two algorithms. SAW method was also used to determine which method is more preferable. The provided results showed the NSGA II algorithm had better performance than NRGA. However, there were no significant differences between performance measures. Several ways can be suggested to extend this study. At first, it is suggested implementing other meta-heuristic algorithms such as multi-objective particle swarm optimization. Second, using other mutation and crossover operators are also recommended. The implementation of the proposed model and solution approach to a real industrial case would also be a considerable extension of this study.

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Appendix 1: Notations, parameters and decision variables

s: Suppliers, *p*: Plants, *d*: Distributors, *c*: Customer centers, *i*: Collection and inspection centers, *k*: Repairing centers, *l*: Recycling centers, *m*: Disposal centers, *t*: Periods

$\widetilde{CS}_{\gamma}^{t}$: Capacity of utilities $\gamma \in \{s,p,d,i,m,l,k\}$ at time period t

FC_{γ}: Fixed cost of opening utilities $\gamma \in \{p,d,i,m,l,k\}$

FJ_{γ}: The number of fixed job opportunities created by establishing utilities $\gamma \in \{p,d,i,m,l,k\}$

VJ_{γ}: The number of variable job opportunities created by establishing utilities $\gamma \in \{p,d,i,m,l,k\}$

TC_{sp}, TC_{pd}, TC_{dc}, TC_{ci}, TC_{im}, TC_{il}, TC_{ik}, TC_{ls}, TC_{kd}: Transportation cost a product from between utilities

EIS_{sp}, EIS_{pd}, EIS_{dc}, EIS_{ci}, EIS_{im}, EIS_{il}, EIS_{ik}, EIS_{ls}, EIS_{kd}: Environmental impacts of shipping a product between utilities

EIP_{p}: Environmental impacts of producing at plant p

EID_{m}: Environmental impacts of disposing at disposal center m

MC_{p}^{t}: Manufacturing cost at plant p at time period t

DC_{m}^{t}: Disposal cost at disposal center m at time period t

RC_{l}^{t}: Recycling cost at recycling center *l* at time period t

BC_{k}^{t}: Repairing cost at repairing center *k* at time period t

$\widetilde{DE}_{c}^{t}$: Demand of customer center *c* at time period t

RY_{t}: Recycling ratio at time period t

RV_{t}: Repairing ratio at time period t

RD_{t}: Disposal ratio at time period t

$\tilde{\gamma}_{c}^{t}$: Reverse ratio at time period t

$O\gamma_{\gamma}^{t}$: 1 if facility $\gamma \in \{s,p,d,i,m,l,k\}$ is to be established at time period t; 0 otherwise

QS_{sp}^{t}, QS_{pd}^{t}, QS_{dc}^{t}, QS_{ci}^{t}, QS_{im}^{t}, QS_{il}^{t}, QS_{ik}^{t}, QS_{ls}^{t}, QS_{kd}^{t}: Quantity shipped between utilities

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- 3rd International Conference on Material Engineering and Smart Materials, Okinawa, Japan, August 11-13, 2018.
- Industrial Engineering and Manufacturing Technologies, Phuket, Thailand, September 21-23, 2018.
- 26th International Conference on Materials and Technology, Portorož, Slovenia, October 3-5, 2018.
- 5th International Conference on Materials, Mechatronics, Manufacturing and Mechanical, Kuching, Malaysia, November 2-4, 2018.
- 3rd International Conference on 3D Printing Technology and Innovations, Rome, Italy, March 25-26, 2019.
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