Multi-criteria design of an innovative frame saw machine based on visual interactive analysis method

Thiết kế đa tiêu chí máy xẻ dạng khung kiểu mới dựa vào phương pháp tương tác và phân tích trực quan

Đặng Hoàng Minh[1,*], Phùng Văn Bình[2], Nguyễn Việt Đức[3]

[1]*Industrial University of Ho Chi Minh City*

[2]*Military Technical Academy*

[3]*Thuy Loi University*

**Email: danghoangminh@iuh.edu.vn*

Tel: +84-28-38940390; Mobile: 01276399799

Keywords:

Frame saw machine; Multi-criteria design; Multi-objective optimization; Visual interactive analysis method.

Abstract

This paper presents a design process of an innovative frame saw machine based on the concept of “multi-criteria product life-cycle quality management”. An advanced life-cycle model was developed to interact and deal with inconsistencies among different stages in the design of this machine. The central synthesis stage in the model is a multi-criteria mathematical model including ***8*** control parameters, ***9*** functional constraints and ***9*** objective functions, which were established by various experts. In order to deal with this multi-objective optimization problem, the authors proposed a novel approach, involving Visual Interactive Analysis Method (VIAM) with an application of single-objective optimization techniques. VIAM assisted in searching for valid and optimal solutions, satisfying technical requirements at different scenarios. Additionally, VIAM can also be widely used in multi-criteria design of other products.

Từ khóa:

Máy xẻ dạng khung; Thiết kế đa tiêu chí; Tối ưu hóa đa mục tiêu; Phương pháp tương tác và phân tích trực quan

Tóm tắt

Bài báo này giới thiệu quy trình thiết kế máy xẻ dạng khung kiểu mới dựa trên việc ứng dụng nguyên lý “quản lý đa mục tiêu vòng đời sản phẩm”. Một mô hình vòng đời sản phẩm cải tiến đã được xây dựng nhằm giải quyết những mâu thuẫn giữa các khâu trong quá trình thiết kế máy xẻ. Khâu tổng hợp là một mô hình toán đa tiêu chuẩn với 8 tham biến, 9 ràng buộc và 9 hàm tiêu chuẩn, được thiết lập bởi các chuyên gia khác nhau. Tác giả đã đề xuất phương pháp tương tác và phân tích trực quan (VIAM) cùng với kỹ thuật tối ưu hàm một chuẩn để giải quyết bài toán tối ưu hóa đa mục tiêu này. VIAM đã giúp cho việc tìm lời tối ưu, đồng thuận, thỏa mãn các yêu cầu kỹ khắt khe khác nhau. Ngoài ra, VIAM cũng có thể được ứng dụng trong việc thiết kế đa tiêu chuẩn các sản phẩm khác.

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1. INTRODUCTION

Today, the wood processing serves as an important industry to promote the development of many countries around the world. Wood before becoming the final product to the consumer needs to go through several stages of processing; one of them is a sawing process of long logs into thin boards. Among commonly-used saw machines in the market, traditional frame saw machine is indicated that it yields higher productivity than others, because many sawblades can be mounted on this machine simultaneously. However, the traditional machine still presents inherent drawbacks such as dynamic imbalance that results in vibration, noise and cutting-speed limitation [1].

In order to tackle with limitations of the traditional one, an innovative frame saw machine with fourbar parallelogram linkage mechanism has been studied and developed lately (Fig. 1). The machine was designed to ensure dynamic self-balancing system; consequently it is able to work steadily at high speed (approx. 3000 rpm) without an extra balancing mechanism [2, 3]. During design and manufacture process, every component of this machine needs to be studied carefully and accompanied by an observation of the entire system, with a final aim to comply with all of quality criteria required by related experts [4, 5]. From a technical point of view, this would be a big challenge, because there might be conflicting objectives or contradictories at different stages of the machine life-cycle, i.e. one objective is improved and another is worsened.

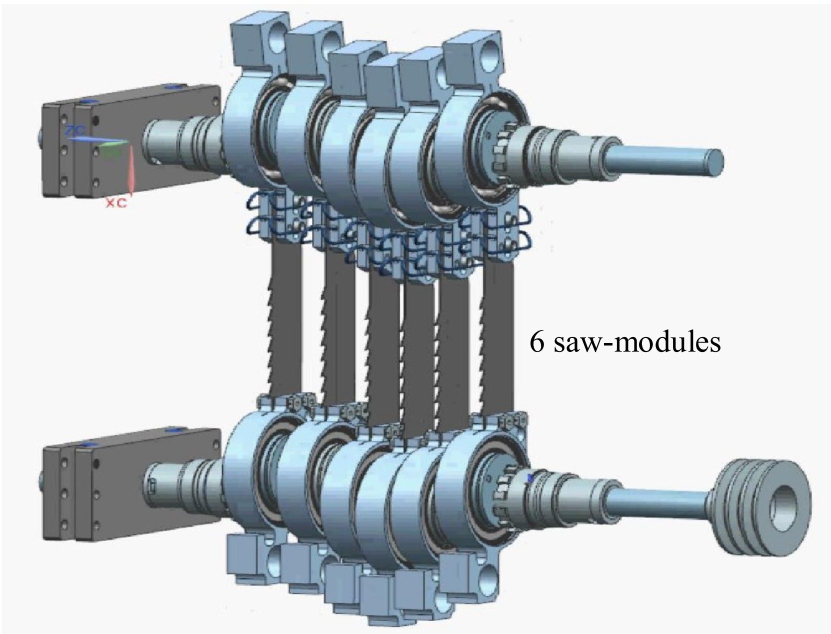

Fig. 1. An innovative frame saw machine with 6 saw-modules

As a result of that during development and manufacture of an innovative frame saw machine, a concept “product life-cycle quality management” needs to be implemented within a unified information model, which supports experts to make sound and reliable decision in real-time (Fig. 2). Thus, in this paper an advanced modelling is proposed by the authors to tackle with the concerned problems [4]. As shown in Fig.2, an additional synthesis stage serves as “a command centre” to analyse and reconcile inconsistencies appeared among manufacturing stages. The synthesis stage is actually a model based multi-objective optimization, which comprises of multiple technical parameters, constraints, and objective functions.

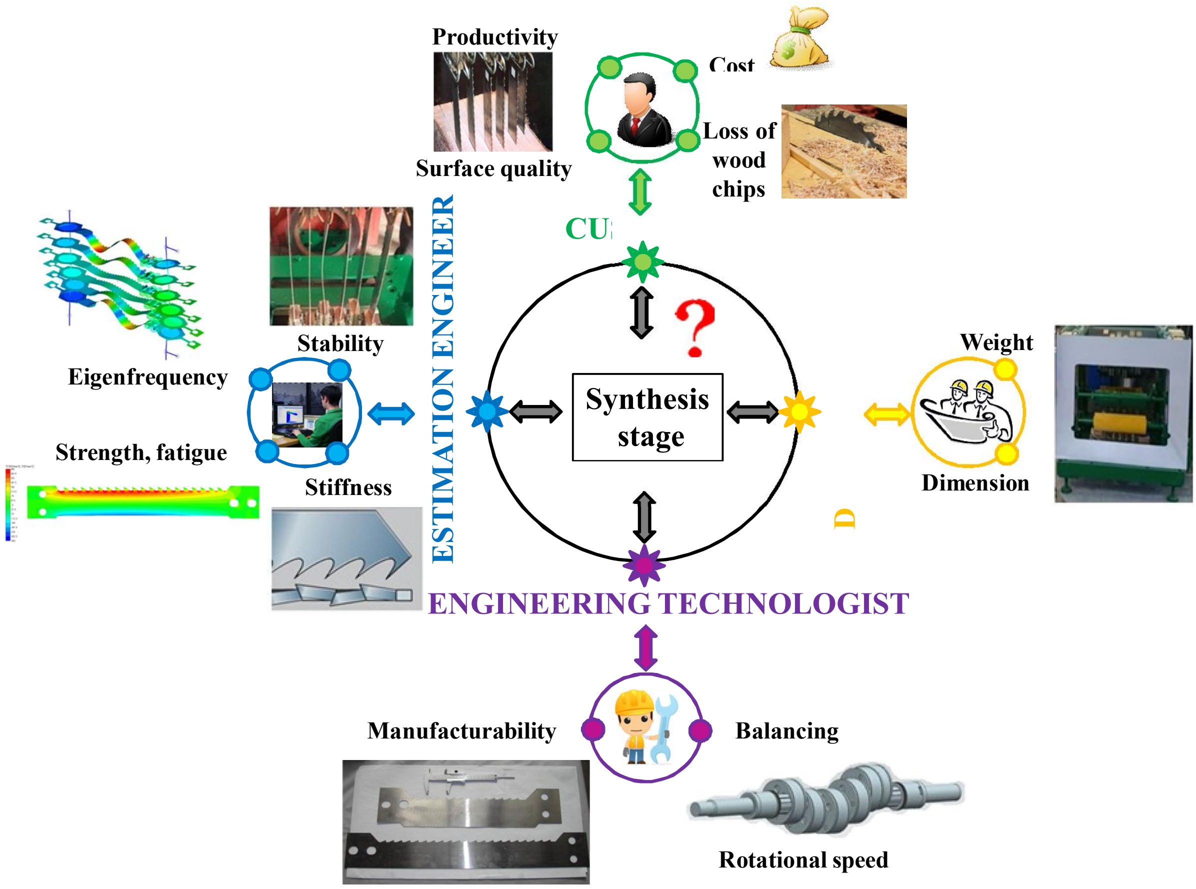

Fig. 2. Complex inconsistencies among manufacturing stages in life-cycle of an innovative frame saw machine

2. SAW MACHINE MODELLING

Multi-criteria model for saw machine is developed by collaboration of various experts in the field. The model consists of *08* parameters, *09* constraints, and *09* objective functions, which are included in Table 1, Table 2, and Table 3 respectively. The details how to build this model were described in the previous publication [6].

Table 1. Control parameters.

Parameters	Minimum value	Maximum value	Units	Definition
α_1	0.03	0.035	m	Eccentricity of the circular motion
α_2	0.06	0.1	m	Saw blade width
α_3	0.001	0.002	m	Saw blade thickness
α_4	0	0.08	m	Eccentricity of saw blade tension
α_5	0.1	0.2	m	Distance h_b
α_6	0	1	kg	Counterbalance mass
α_7	500	2000	N	Tension force magnitude
α_8	2000	3000	rev./min.	Shaft rotation speed

Table 2. Constraints.

Symbol	Requirement	Explanation
f_1	≤ 0	Requirement for an absence of resonance
f_2	≥ 0	Stability requirement of sawblade under inertial forces
f_3	≤ 0	Balance state of the saw-module
f_4	≥ 0	Tensile force requirement
f_5	≥ 0	Strength requirement of sawblade
f_6	≥ 0	Fatigue requirement of sawblade
f_7	≥ 0	Initial rigidity requirement of sawblade
f_8	≥ 0	Stability requirement of sawing processes
f_9	≥ 0	Specified requirement (real value exists) for criteria Φ3

Table 3. Objective functions.

Criteria	The direction of improvement	Explanation
Φ_1	MIN	Total mass of the sawblade and the counterbalances
Φ_2	MIN	Overall dimension
Φ_3	MAX	First natural frequency of the saw-module
Φ_4	MAX	Critical speed of shaft rotation
Φ_5	MIN	Tension force magnitude
Φ_6	MAX	Operating speed of shaft rotation
Φ_7	MAX	Stability of sawing processes
Φ_8	MAX	Initial rigidity of unstrained sawblade (in the absence of sawing force)
Φ_9	MIN	Sawblade thickness

3. METHOD AND RESULTS

3.1. Solving method

Dealing with conflicting objectives within life-cycle of an innovative frame saw machine presents a complex task on multi-criteria management. If the conventional multi-objective optimization methods are used, it might make the task becoming out of its essence. The reason is that most of these methods implement the idea of converting the objectives into an equivalent function (or scalar methods) by using many techniques such as weighted minimax (maximin), compromise programming, weighted sum, bounded objective function, modified Tchebycheff, weighted product, exponential weighted sum, etc [7, 8]. However, most of them did not pay attention on arranging an interactive panel, which supports experts to be aware of feasible area of objectives. This leads to the fact that there is no basis to evaluate and analyse the resultants. Besides, these methods are capable of searching several solutions in one-way direction; it means that although the resultant from every algorithm is Pareto solution, it might not be accepted by experts. For instance, there is a case that an objective yields a very good result, but normally it is not necessary; while, another one has not yielded a valid solution yet. This shows that there is no professional intervention or control from experts during solution search, that the obtained solution is barely the result from a fixed algorithm and no more beyond that.

In this paper, the author proposes a Visual Interactive Analysis Method or VIAM in order to solve the aforesaid existing problems. The main idea of VIAM is to use the single-objective optimization techniques as a tool with the aim to find valid solution of multi-criteria management task, complying with technical requirements from experts. VIAM is established by using method of successive concessions together with an interactive panel. Algorithm scheme of VIAM is described in details in another publication [4], basically it includes following steps:

1. Determine limits of parameters [minα_i, maxα_i], constraints and objective functions Φ_i, i =1…M., where M - number of objective functions
2. Deal with the problem of single-objective optimization for every criterion, define MAXΦ_i and MINΦ_i. For convenience, the maximum values are placed with negative signs.
3. Determine the order of criteria importance. Assumed that the priority order of the criteria is from the first to the Mth ones.
4. Assign an expert (decision-maker), who will set the threshold [Φ_I] for the most important criterion, based on this it is possible to determine the minimum value of the rest criteria minΦ_i.
5. Check whether the minΦ_i complies with the requirement of experts or not. If not, it is necessary to adjust the threshold [Φ_I] up to the moment that there is a desirable result.
6. Repeat the Step 4 and 5 up to the moment that the threshold for $(M$-1) criteria are specified.
7. Based on the given $(M$-1) constraints, it is possible to define the optimal coordinated solutions among experts.

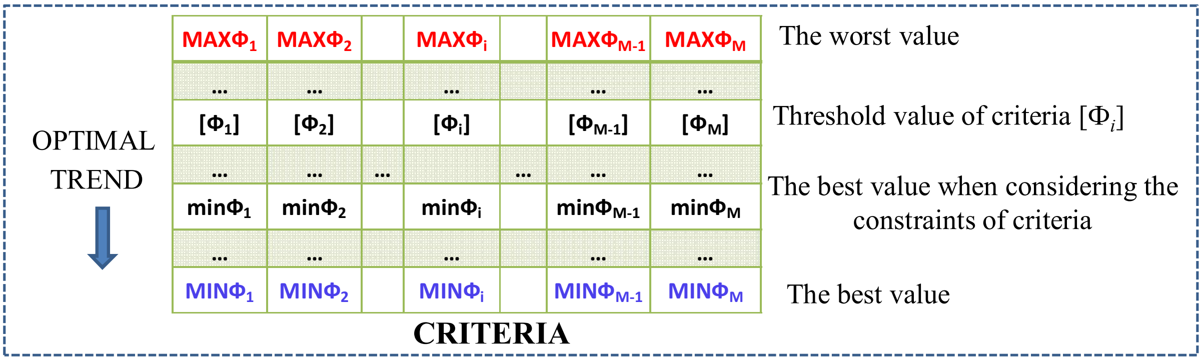

Fig. 3. Interactive panel, the maximum values of objective functions are given with negative signs

3.2. Obtained results

Based on the algorithms in VIAM, the authors have developed computational program named VIAM_SAW used for multi-criteria design of an innovative frame saw machine. This program helped to determine rational parameters for the design. Criteria of the machine, threshold and limits of control parameters are included into interactive panel, as shown in Fig. 4. The difference between these criteria and the ones of current existing saw machines is provided in the panel; positive value - the criterion is improved, negative value - the criterion is worsened, and “zero” value - the criterion is unchanged.

The first scenario assumes that based on the client’s requirement experts (decision-makers) selected seven the most important criteria (or objective functions) $\{\Phi_1,\Phi_3,\Phi_4,\Phi_5,\Phi_6,\Phi_7,\Phi_9\}$, while values of the rest criteria are not restricted. The solution search process is carried out by using a foresaid VIAM. The experts interfere only in case of discussion for determining the threshold of criteria. Importance grade of every criterion is presented by using threshold values (in square parenthesis). The rational coordinated solutions are given in Fig. 4 and Table 4. The results from this scenario indicate that five criteria are improved, while the criterion on mass is improved up to 63%. Though, there are still three criteria worsened.

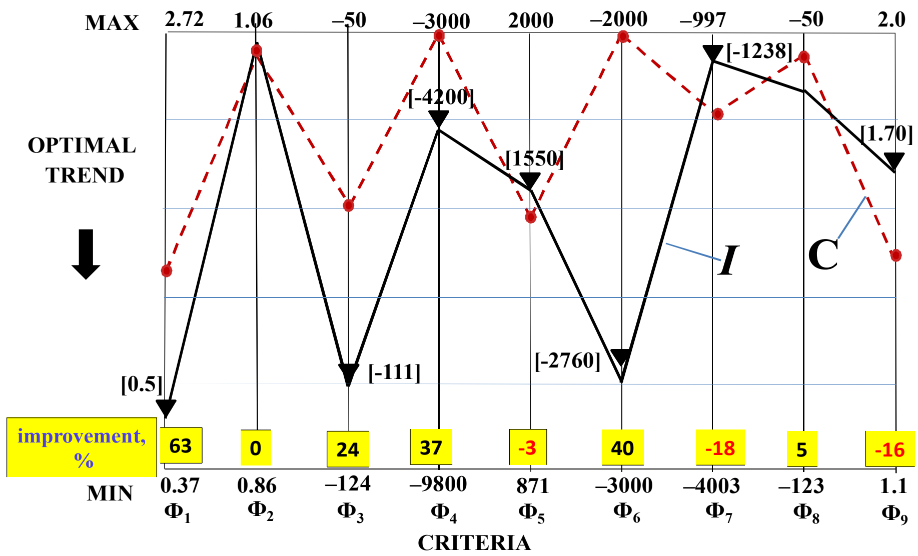

Fig. 4. Scenario 1 - threshold values for 7 criteria $\{\Phi_1, \Phi_3, \Phi_4, \Phi_5, \Phi_6, \Phi_7, \Phi_9\}$.
I - Scenario 1, *C* - current existing machine

The second scenario assumes that experts focus on 4 criteria such as $\{\Phi_1, \Phi_5, \Phi_6, \Phi_9\}$ and desire to make them as good as possible. The calculation results show that three of these four criteria are improved essentially from 35% to 49%, as shown in Fig. 5.

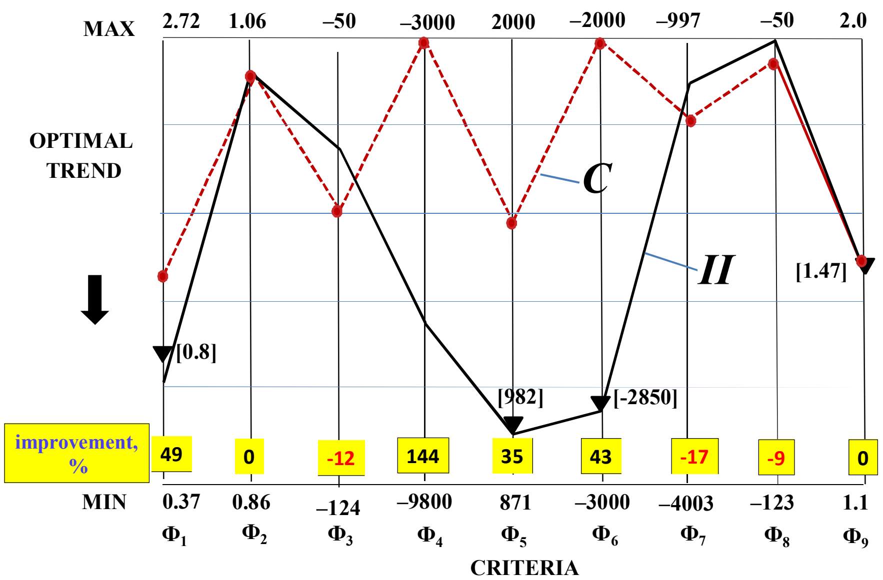

Fig. 5. Scenario 2 - limits for 4 criteria $\{\Phi_1, \Phi_5, \Phi_6, \Phi_9\}$.
II - Scenario 2, *C* - current existing machine

Table 4. Rational coordinated solutions from all 3 scenarios

Variants	*i*	1	2	3	4	5	6	7	8	9
MAXΦ$_i$		**2.72**	**1.06**	**-50**	**-3000**	**2000**	**-2000**	**-997**	**-50**	**2**
MINΦ$_i$		**0.37**	**0.86**	**-124**	**-9800**	**871**	**-3000**	**-2000**	**-4003**	**1**
Current existing machine	α_i	0.030	0.08	1.47	0.04	0.160	0.50	1500	2000	-
	Φ_i	**1.35**	**1.050**	**-90**	**-3047**	**1500.0**	**-2000.0**	**-1507**	**-55**	**1.47**
Scenario 1	α_i	0.030	0.060	1.70	0.002	0.200	0.07	1550	2798	–
	Φ_i	**0.50**	**1.054**	**-111.6**	**- 4163**	**1550.3**	**-2798.3**	**-1238**	**-57.5**	**1.70**
Scenario 2	α_i	0.030	0.062	1.468	0.061	0.196	0.18	982	2852	–
	Φ_i	**0.695**	**1.046**	**-79.1**	**- 7427**	**982.0**	**-2852**	**-1257**	**-50.2**	**1.47**
Scenario 3	α_i	0.033	0.079	1.47	0.058	0.151	0.31	1267	2862	–
	Φ_i	**1.04**	**0.962**	**-80.0**	**- 7263**	**1267.9**	**-2861.7**	**-1584**	**-55.5**	**1.47**

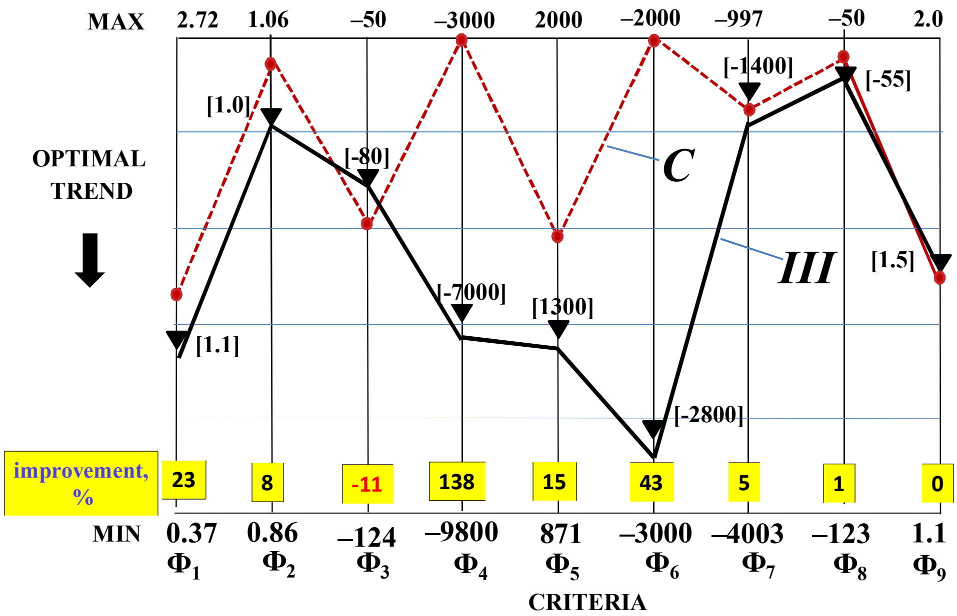

Fig. 6. Scenario 3 - limits for all 9 criteria.
III - Scenario 3, *C* - current existing machine

The third scenario assumes that experts focus on all 9 criteria. The results show that only seven of them are improved, while the criterion on mass Φ_1 is improved 23%, speed Φ_6 43%, on the contrary the criterion on geometry Φ_3 is worsened 11% (

Fig. 6). These results comply with strict requirement of experts in the design process and they are used for manufacturing the saw machine later on.

According to the obtained solutions, various design schemes of sawblade have been created, as shown in Fig. 7. Every solution corresponds to one of the possible manufacturing options for an innovative frame saw machine.

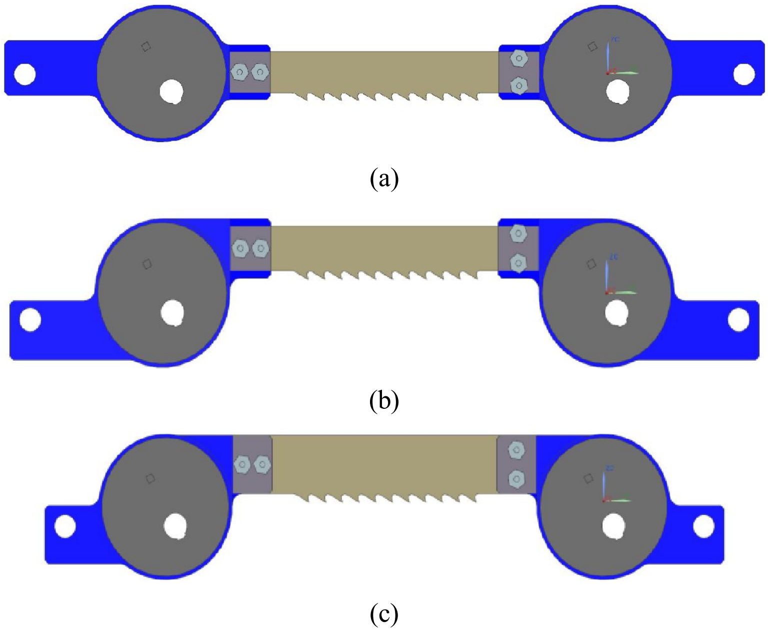

Fig. 7. Design schemes of sawblade corresponding to obtained solutions at Scenarios I (a), II (b) и III (c)

4. CONCLUSIONS

Based on results obtained from this paper, following conclusions can be withdrawn:

- VIAM has been used relevantly for defining and controlling the threshold values of objective functions or criteria, evaluating their mutual influences, and indicating the rational criterial constraints at which there are coordinated solutions for designing an innovative frame saw machine.
- Computational program VIAM_SAW supported properly the decision-making process for multi-criteria design of the saw machine
- Calculation results not only made solution search for design of the machine easier, but also provided guidelines for design improvement.

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