An Affordance-based Approach for The Design of Customized Product Non-standard Part

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Abstract: In this paper we develop an affordance-integrated approach to support design of the customized product non-standard part from conceptual period to detailed period. Firstly, the part affordances are identified by geometrical correlation analysis and shown by liaison graph. Secondly, a force transmission based method is developed to identify the main design parameters of a part, at the same time the design parameters and user requirements both can be mapped into the affordances. In turn, these affordances can be used as a bridge to construct the mapping relationship between the user requirements and the design parameters. In the end, both the force transmission method and the mapping relations are used to construct the detailed model of the non-standard part. A rear platen from the injection molding machine is employed to demonstrate the proposed approach and the result shows that this method can be feasible and useful in product design.

Keywords： Affordance-integrated design, liaison graph, force transmission, detailed design

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1 Introduction

Customized products refer to the products manufactured to meet users' specific needs. Because of intensifying competition and diversified requirements, more and more companies are striving to offer more customized products with greater rapidity. Since many parts of the products are customized and non-standard, rapidly designing and manufacturing the non-standard parts is essential for the companies to succeed in the fierce market competition.[1] For a customized non-standard part, the design flow undergoes a process from idea formation to conceptual design, and then comes into detailed design. For design problems concerning varied complexity, different disciplines, the design period from conceptual period to detailed design is the most important period in product design.

Conceptual design has been well investigated. Barnum *et al*. (2010) proposed an interactive and computationally assisted methodology for capturing and incorporating designer preferences into a numerical search for design concepts.[2] Burgess (2012) proposed a backwards design method for mechanical conceptual design, and exploited the principle that it is easier to critique and modify a design than to create a fully working solution at one go.[3] Stone *et al*. (2000) introduced a functional basis language to characterize product functions and used the functions to comprehensively describe the mechanical design space.[4] There are also some other design methods that are used in conceptual design such as morphological charts, design repositories, analogy, and function-failure reasoning.[5-8] These methods above can give an output of user requirements, basic functional structures, candidate conceptual design solutions and evaluation of the solutions for the detailed design implementation.

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Simultaneously, detailed design also has attracted many researchers' attention. Govindaraj V *et al.* (2005) demonstrated the application of genetic algorithms for the optimum detailed design of reinforced concrete continuous beams, and the optimum design method satisfied the strength, serviceability, ductility, durability and other constraints related to good design in detailed practice.[9] Nomen *et al.* (2013) exemplified the detailed mechanical design process of the beam dump, in which the shielding and the lead shutter were taken into account to constrain working conditions and other external loads.[10] Marcuzzi *et al*. (2010) depicted an overview of the SPIDER beam source design in terms of the main design choices, aiming at reaching a balance among physics, optics, thermo-mechanical, cooling, assembly and electrical requirements.[11]

Many efforts have been dedicated to explore the connection between conceptual design and detailed design. Christie *et al*. (2012) created an advanced systems design suite (ASDS) with an immersive virtual reality (VR) environment to ease the creation and assessment of conceptual design prototypes individually.[12] Renner *et al*. (2015) presented a conceptual design and feasibility analysis for oversized grain harvesting combine headers with dynamic topology by using the ASDS.[13] The axiomatic design process provided a prescriptive way to address design detail progressions from customer needs to function requirement formation, design parameter set up and process variable implementation.[14]

However, the existing design methods are focused on either conceptual design or detailed design. Although many researchers have done lots of attempts on the transmission from conceptual design to detailed design, those attempts were merely focused on transmitting some functional structures. In fact, the functional structures are inadequate to connect the two periods not to mention their innate complexity makes it harder to draw the correlation from a concept to concrete structure of the part, especially for the non-standard parts. Besides, the existing design knowledge may not satisfy the requirements for the new features designed, thus it is very important for the designers to perceive the relations between user requirements and feature parameters. The perception can help to reduce the time of constructing complex functions between the user requirements and the feature parameters, besides, the relation between the new features and user requirements can be acquired well.

Herein, we develop an affordance-integrated approach for the design of customized product which implement the smooth transition from the conceptual period to the detailed period. For the following sections in this paper, the related work in the literature were first reviewed in detail in Sec.2. Then in Sec.3, we introduced the affordance-integrated methodology for part design. In Sec.4, this method was applied for the design of a rear platen of the clamping mechanism to evaluate its effectiveness. In Sec. 5, some conclusions were summarized and their practical and commercial perspectives were pointed out.

2 Previous work

The concept of affordance was originally proposed as what the environment "provides or furnishes" to an animal.[15] Norman (2013) explored the relationship as it exists between people and objects, thus affordances are defined as a set of action opportunities provided by an object, a chair provides the opportunity for sitting, a cup provides the opportunity for drinking.[16] Maier and Fadel (2001) first identified affordances as a basis for design.[17] In simplest terms, an affordance is a possible way of interacting with a product. For example, regardless of designer intent, a mechanical part with a convex and a flat surface affords a matching nut to match on. Then researches began to focus on affordance-based design integration. Consequently, methods for designing particular affordances and affordance-based design processes were created to generate design specifications. Common affordances can be identified and formalized by formalization rules which were used as the formalization of the design problems.[18,19]

Affordances were classified into two different versions (temporary and stable) by Borghi and Riggio (2009), whereas Bub *et al*.(2009) categorized them as functional and volumetric.[20] In addition, Srivastava *et al*. (2013) divided affordances into types of manipulation opportunities, effect opportunities, use opportunities, and activity opportunities.[21] Affordances are defined as positive when they are helpful to users, otherwise negative.

Finding the affordances of a concept or an existing product design is as difficult as the development of the function that map the user requirement onto the design specification. Maier and Fadel (2001) took the advantages of the designer's experiences and design knowledge in his/her brain to analyze and determine the affordances.[17] Nevertheless, the difficulty designers encounter when trying to design a new part for the product can make them confused, since the part has many correlations with other parts. Thus a part-affordance based design method is proposed by Chen *et al.* (2013) in order to capture detailed design knowledge.[22] They defined part-affordance as a perceived interplay relation of a part with another entity in any of its lifecycle periods. Huang *et al*. (2014) proposed a formal approach for detailed design process planning in collaborative environment.[23] And they used part affordance to derive the dependency knowledge among design parameters and generated the part affordance constraint matrix to help designers plan the detailed design process. The part affordance method used both in knowledge reuse and detailed design process planning showed well in design process planning system.

Despite of many researches on this topic, tracking the routine from concepts to detailed design still face many challenges and sincerely need effective design approaches. As mentioned before, to bridge a connection between the two periods often includes various implicit factors, so it is reasonable to apply affordance-based method in non-standard part design process.[24]

3 Affordance-based method for non-standard part design

Affordance-based design is started from the point of user requirements and helps to form a new non-standard part, the part can be represented by several design parameters and constrain qualifications. But in conceptual design, the correlation between user requirements and structure characteristics is hard to achieve by traditional methodologies (e.g., function method, design structure matrix). Thus the affordance-based design method is proposed to relate user requirements to design parameters for the non-standard parts, and the framework of this method is shown in Fig.1.

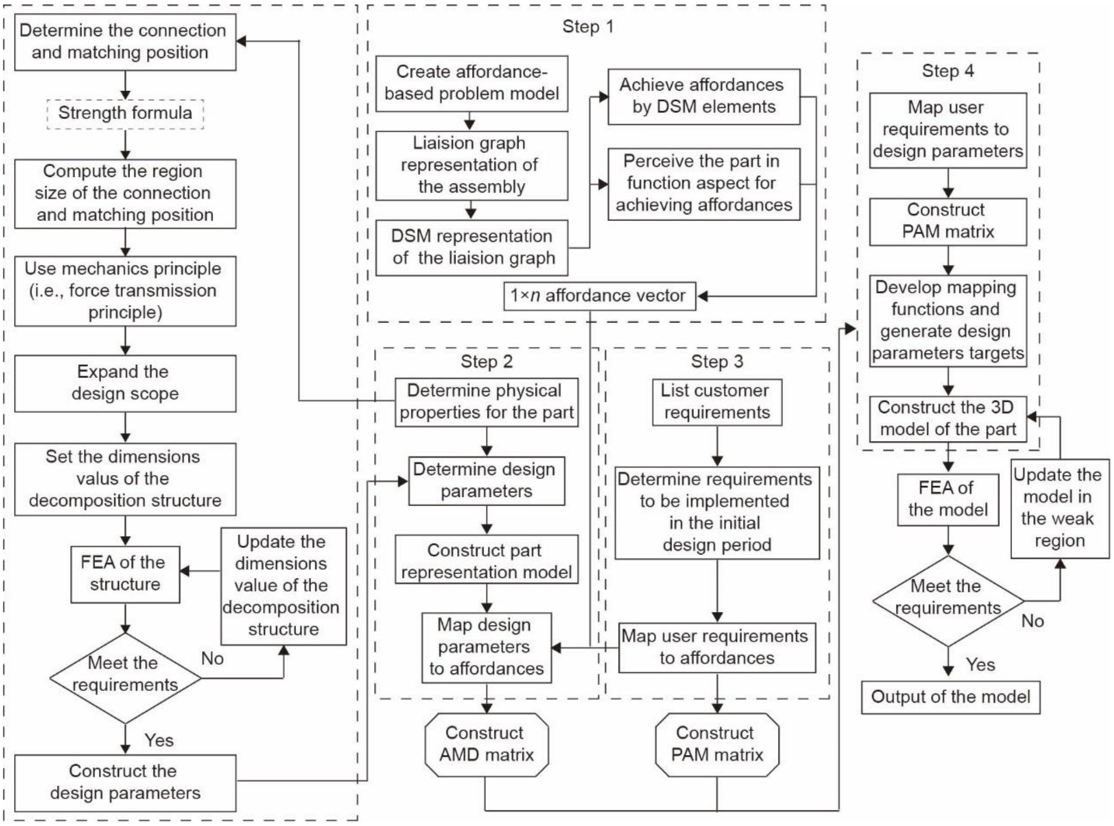

Fig. 1 Affordance-based design method flowchart for the non-standard part

3.1 Create affordances for a customized non-standard part

Artifacts-user affordances (AUAs) and artifact-artifact affordances (AAAs) are used to represent the design information and geometrical correlation analysis is introduced to describe the paradigm of the affordances. Geometrical correlation describes geometrical relation among components as physical connections, size, fastening, verticality, parallelism, concentricity and other factors. And it can be modified by affordance-terminology to represent the affordances (i.e. interplay between the subject and the object). Liaison graph is used to express the geometrical correlation among structure parts clearly, which is shown in Fig. 2.

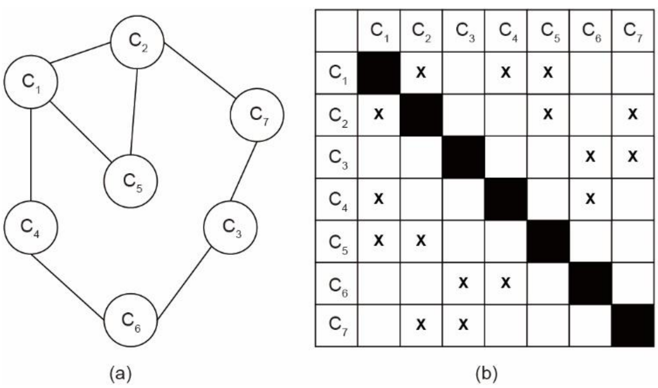

Fig. 2 Geometrical relations among the parts: (a) a liaison graph; (b) basic DSM

The geometrical relation among different parts is clearly shown through the liaison graph. Taking C_3 as an example, it has geometrical relations with C_6 and C_7, thus C_3 can affords C_6 and C_7 by some actions in affordance expression. In the assembly of a product, this method can help to get all the affordances, and these affordances can be represented in an $n\times1$ vector.

3.2 Map design parameters and user requirements to affordances

Firstly, the non-standard part is described with geometrical parameters and physical properties, and the part can be divided into a physical sub-model and a structural sub-model. The physical properties, such as the material, density, tensile strength, yield strength, elongation, and safety coefficient are determined to construct the physical sub-model.

Secondly, the basic design parameters are determined. Because most of the non-standard parts are used to bear and transmit the loads, bear the torque, accommodate other parts and so on. The features of contact faces, mating holes, the cavity, ribs, and scaffolds are generally the force transmission starting point, thus these features can be the starting characteristics to design. Herein the force transmission principle is used to determine the design parameters. Force transmission is an intrinsic property of the object. And the force is transmitted by the inner interaction of the atoms in the metal part, whereas the force transmission between different parts are executed by stretching or squeezing on the contact faces. According the force transmission principle, features such as contact faces, mating holes are determined firstly, then the support framework (e.g. the panel, the connect beam) is added to connect the determined features and the geometrical information of the support framework is constrained by the size requirements and physical properties. Ultimately, when the geometrical information is determined, finite element analysis (FEA) should be used to test the efficiency.

The determined design parameters can be used to represent the structural sub-model of the non-standard part, thus the representation of part information model is constructed by physical and structural sub-models. The model is shown in Fig.3.

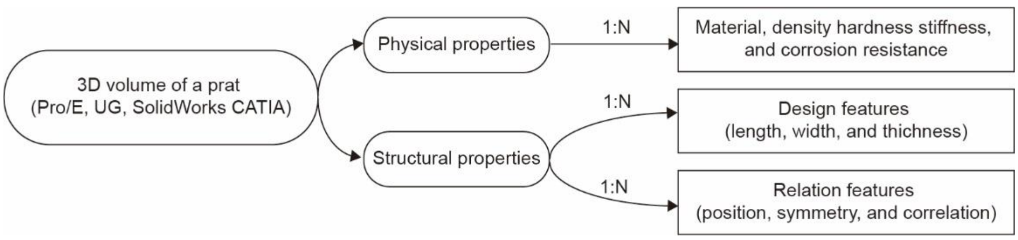

Fig. 3 The part representation model

The design parameters should be mapped to the affordances, and Eq. (1) formally represents a relationship between affordances and design parameters (i.e., the realization of an affordance is a function of the design specifications). Traversing each of the design parameters to find out whether it influence the affordances or not, this will help ensure a complete mapping between design parameters and affordances.

$$A_x = Map(DP_1, DP_2, \cdots, DP_r)\,. \qquad (1)$$

Customers purchase a product because of useful affordances and their requirements (e.g. machining precision, stiffness, velocity, and anti-vibration) are represented by performance items. Though there are large amount of data that could be collected from different customers, a specific customized non-standard part always has limited special performance metrics. Eq. (2) formally depicts the relationship between affordances and part performance metrics (i.e., the realization of an affordance is a function of the customer requirements).

$$A_x = Map(P_1, P_2 \cdots, P_l)\,. \tag{2}$$

Designers traverse the design parameters to make sure which affordance they may influence and then construct the affordance to design-parameters matrix (ADM) to represent the relations. Similarly, designers traverse the affordances to make sure which performance it may influence and construct the performance to affordance matrix (PAM). The relations are shown in Fig. 4.

	A_1	A_2	A_3	⋮	A_n
DP_1		1			
DP_2			1	1	
DP_3			1		
⋮					
DP_m		1			

	A_1	A_2	A_3	⋮	A_n
P_1		1			1
P_2	1				
P_3			1		
⋮					
P_l		1			1

Fig. 4 Affordance relation matrix: (a) ADM; (b) PAM

3.3 Map performance to design parameters

After creating the ADM and PAM, the mapping relations between design parameters and performance metrics can be achieved in a design parameter to performance matrix (DPM). See Fig. 5 for a general form.

	P_1	P_2	P_3	⋮	P_l
DP_1	1	2			
DP_2			1		
DP_3			2		3
⋮					
DP_m		1			

Fig. 5 parameters-to-performance matrix

Take the ADM and PAM in Fig. 6 as an example, the DPM is constructed using the following steps:

Step 1. After traversing the PAM, we can find that P_1 impacts A_2 and A_3, P_2 impacts A_4, P_3 impacts A_1 and A_3, P_4 impacts A_2.

Step 2. After traversing the ADM, we can find that A_1 is impacted by DP$_3$, A_2 is impacted by DP_1 and DP_4, A_3 is impacted by DP_2 and DP_3, A_4 is impacted by DP_2. So P_1 has the potential to influence design parameters DP_1, DP_2, DP_3 and DP_4. Since A_4 gives a one-to-one mapping between P_2 and DP_2, so P_2 must influence the design parameter DP_2. Both of A_1 and A_3 are impacted by DP_3, meanwhile P_3 impacts A_1 and A_3, so P_3 must influence DP_3 and may influence D last we can achieve that P_4 has the potential to influe 1 and DP_4.

	A_1	A_2	A_3	A_4
P_1		1	1	
P_2				1
P_3	1		1	
P_4		1		

	$A1$	$A2$	$A3$	$A4$
DP_1		1		
DP_2			1	1
DP_3	1		1	
DP_4		1		

	$P1$	$P2$	$P3$	$P4$
DP_1	2			2
DP_2	3	4	3	
DP_3	3		1 3	
DP_4	2			2

Fig. 6 an example of the matrix mapping relation: (a) PAM; (b) ADM; (c) DPM

Based on the DPM (in Fig. 6), a designer can clearly see what performance metrics drive design parameters and they can also identify the affordances which influence the design parameters and the performance metrics. In Fig. 6, the numbers in the smaller filled box show that the corresponding order of the affordance sequence can indicate the relation between the individual row of the design parameters and the column of performance metrics. The larger solid line box means the corresponding performance metrics have a firm relation with the design parameters, while the dashed line box represents a relatively weak relation. So we can get the functional representations as follows:

$$\begin{aligned}
&A_1 \; indicates \; P_3 = f(DP_3), \\
&A_2 \; indicates \; P_1 = f(DP_1, DP_4), \\
&\qquad\qquad\quad\;\; P_4 = f(DP_1, DP_4), \\
&A_3 \; indicates \; P_1 = f(DP_2, DP_3), \\
&\qquad\qquad\quad\;\; P_3 = f(DP_2, DP_3), \\
&A_4 \; indicates \; P_2 = f(DP_2).
\end{aligned} \tag{3}$$

3.4 Construct the geometrical model with the DPM

During the period of identifying the design parameters, the approximate design parameters are determined, but they aren't clearly related to the performance items, thus the DPM is used to help modify geometry model to satisfy user requirements. By the rules generated in the DPM, designers modify the model iteratively to meet design objective. Customized non-standard parts need high stiffness, high rigidity to fulfil their utilities of bearing loads and transmitting energy. So their design should be undertaken on the bearing area (e.g. connect faces and mating holes) firstly. Then the panel or beam are added to connect the features designed.

Take a connect-rod for example, as shown in Fig.7. The diameter of the pin hole is determined first based on the torque demand, the dimensions of A_1, A_2, A_3 are approximately determined. However, these three parameters have a large influence on the torque performance through the analysis of the DPM, thus the dimensions should be modified to meet the performance requirements. The beam is added to the cyclic features based on the length requirement, the basic connect-rod is then designed.

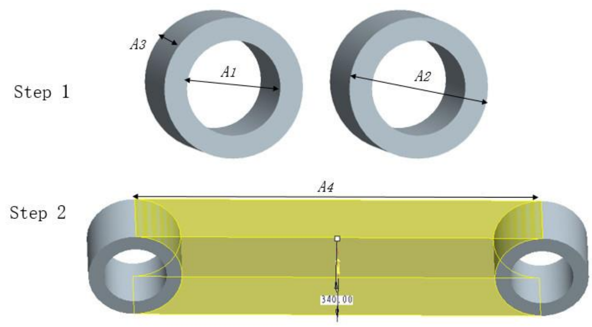

Fig. 7 A case for a connect-rod

4 Case study of a rear platen for the injection molding machine

This section demonstrates that the method represented in Section 3 is applied to a rear platen—a key structure part of an injection molding machine. The clamping mechanism and its major components of a molding machine is shown in Fig. 8, and the components of the clamping mechanism are listed in Table 1. Based on the liaison graph in Fig. 9, the DSM is constructed (Fig.10).

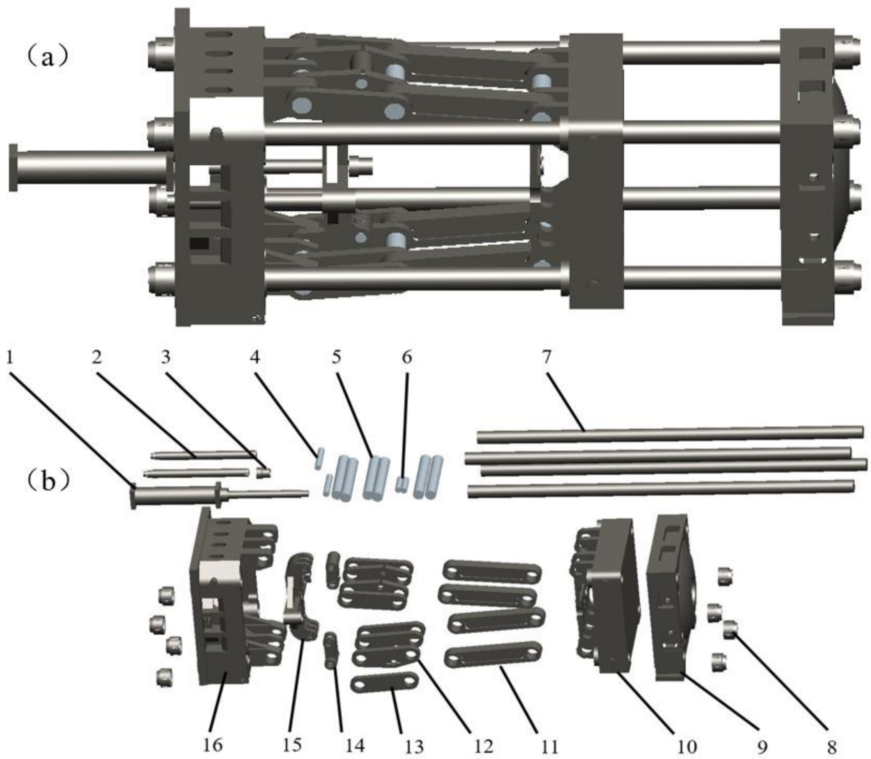

Fig. 8 components of the case: (a) the clamping mechanism of an injection molding machine; (b) its explosion modeling in Pro/E

Table 1. List of components of the clamping mechanism

No.	Component	No.	Component
1	Clamping cylinder	9	Front platen
2	Guide rod	10	Moving platen
3	Cylinder nut	11	Long linkage rod
4	Cross-head connecting pin	12	Clamping arm A
5	Clamping arm connecting pin	13	Clamping arm B
6	Short linkage rod connecting pin	14	Short linkage rod
7	Tie bar	15	Cross head
8	Tie bar nut	16	Rear platen

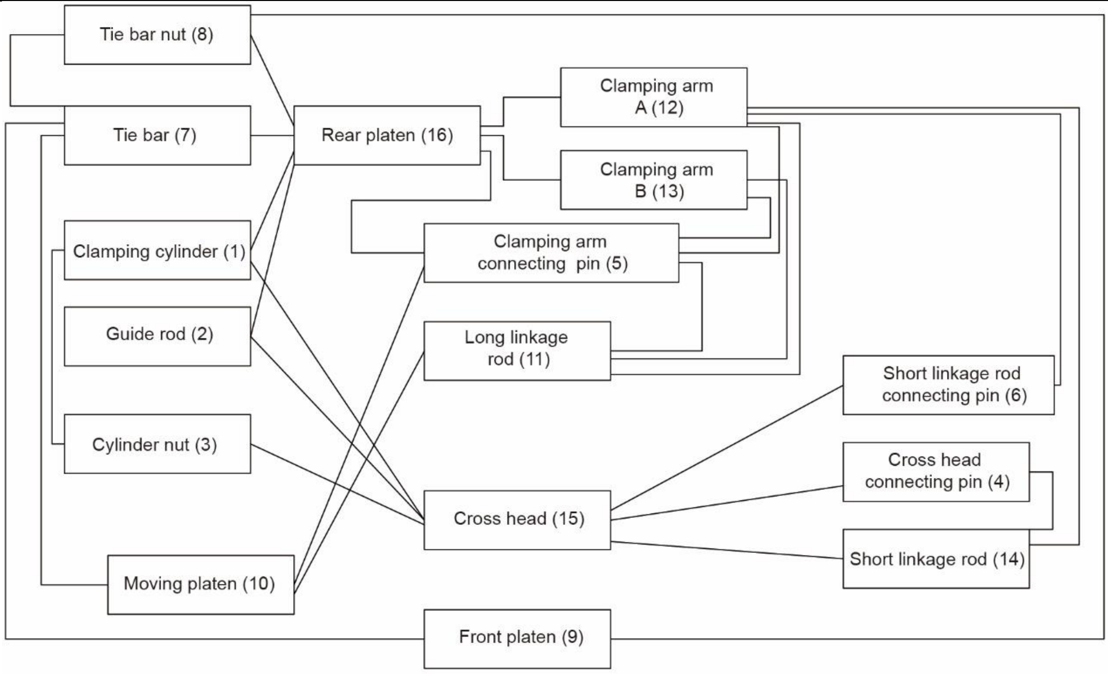

Fig. 9 The liaison graph of the clamping mechanism of an injection molding machine

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1			X												X	X
2															X	X
3	X														X	
4														X	X	
5										X	X	X	X			X
6												X			X	
7								X	X	X						X
8							X		X							X
9							X	X								
10					X		X				X					
11					X											
12					X	X					X			X		X
13					X											X
14				X								X			X	
15	X	X	X	X		X								X		
16	X	X			X		X	X				X	X			

Fig. 10 Basic DSM of the clamping mechanism

4.1 Create affordances for the rear platen

From the DSM in Fig. 10, the affordance model for the rear platen can be constructed. From the DSM, part (1, 2, 5, 7, 8, 12, 13) have a connection relation with the rear platen. Using affordance representation, part affordance representation is constructed, as shown in Fig. 11. These 10 affordances (*n*=10) are now used to identify design parameters.

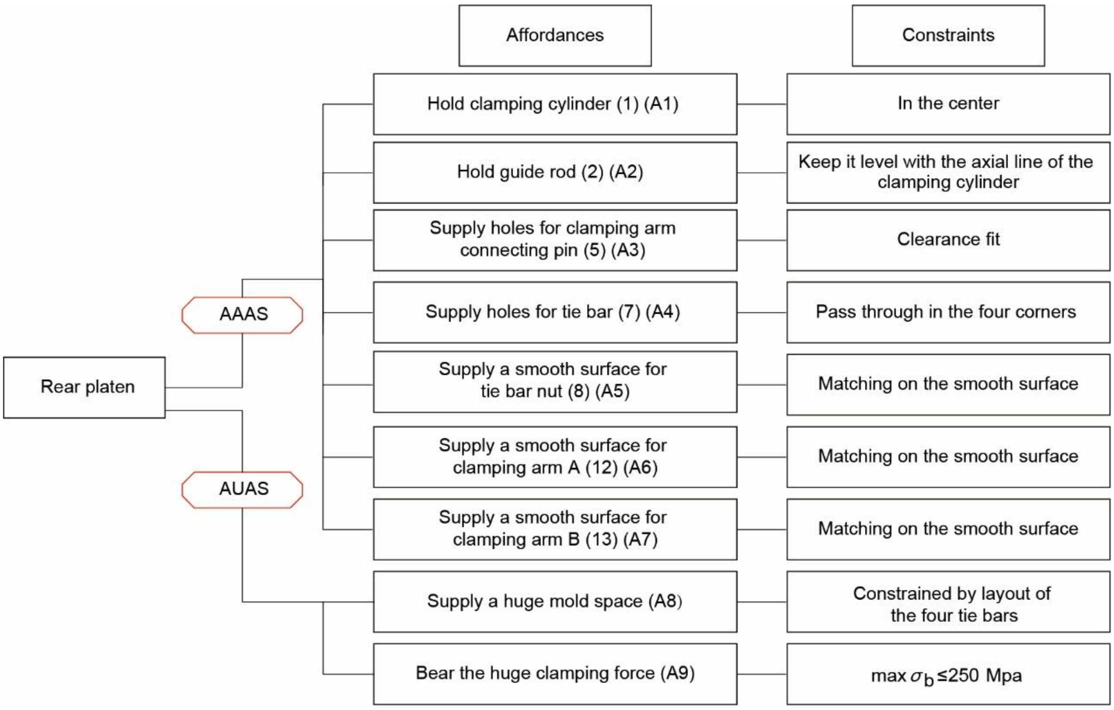

Fig. 11. Rear platen desired affordance model

Then customers' requirements should be gathered and related to the rear platen. For a specific clamping mechanism of an injection molding machine, the requirements related to the rear platen may be classified in Table 2.

Table 2. List of customer requirements

Requirements item	Value/or descriptions
Clamping force(P_1)	40,000,000/*N*
Open stroke(P_2)	2,350*mm*
Mold size(P_3)	2000×2000mm^2
Quality(P_4)	Lightweight
Stiffness(P_5)	High
Anti-vibration(P_6)	High

4.2 Map design parameters and customer requirements to affordances

Based on the rear platen desired affordance model, design parameters for the platen can be determined.

Step1. Determining the physical properties of the rear platen, the material is QT500-7(i.e., density: 7250 kg/m^3, tensile strength: 500Mpa, yield strength: 320Mpa, elongation: 7%, safety coefficient: 2.0).

Step 2. Determining the design parameters of the rear platen.

Based on user requirements shown in Table 2, designers first determine the hole for inserting the tie bar. Generally, the tie bar is the material of 40Cr (i.e., tensile strength:980Mpa, elongation:>9%). In continuously reciprocating motion of the open/close stroke, some poor working conditions such as bending, shearing et al., may occur during operating, so the allowable stress of the tie bar should be chosen with the value not large than 250Mpa. After several attempts, the diameter is determined as an integer of 370 mm. Based on Eq. (4), the diameter of the convex, which is matching with the tie bar nut can be worked out, where *P* is the allowable stress of rear platen panel, d is the diameter of tie bar, *D* is the unknown diameter of the convex and *F* is the clamping force, thus *D* can be calculated out to be 800 mm.

$$P\times\pi(\frac{D^2-d^2}{4})=\frac{F}{4}\cdot \qquad (4)$$

(1) Since they are standardized in series, the dimensions of a chosen mold are determined. Based on the data provided by Zhejiang Sound Machine Manufacturing Co., Ltd. We choose 2400*2200 mm^2 as the space, the panel framework dimensions can be determined. Then the clamping cylinder rod diameter is selected as 220 mm, which is located in the center of the panel. The guide rod is not determined so far.

(2) The open stroke is approximately 1.5 times the length of the rib, so the length of the rib is1500 mm. Based on the requirements of the statics properties, the thickness of the rib can be achieved. After several attempts by experienced designers, the dimension of the rib is approximately determined. And the dimension information and the FEM analysis result are shown in Fig. 12.

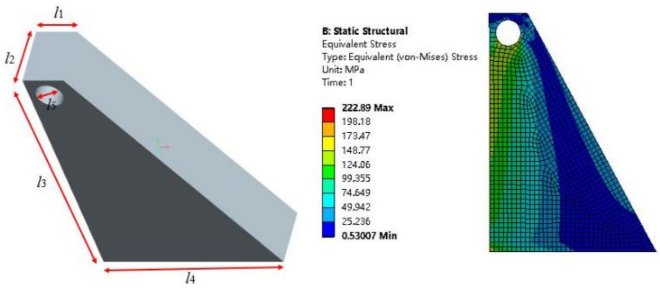

Fig. 12. Geometry information and FEM result of the rib

In Fig. 12, l_1, l_2, l_3, l_4 and l_5 are determined as 250 mm, 320 mm, 1800 mm, 1100 mm, 330 mm, respectively. After three steps, the rear platen representation model is constructed, which is shown in Fig. 13. Based on the rear platen representation model, design parameters can be extracted which are listed in Table 3. And the affordance to design parameters matrix is constructed shown in Fig. 14.

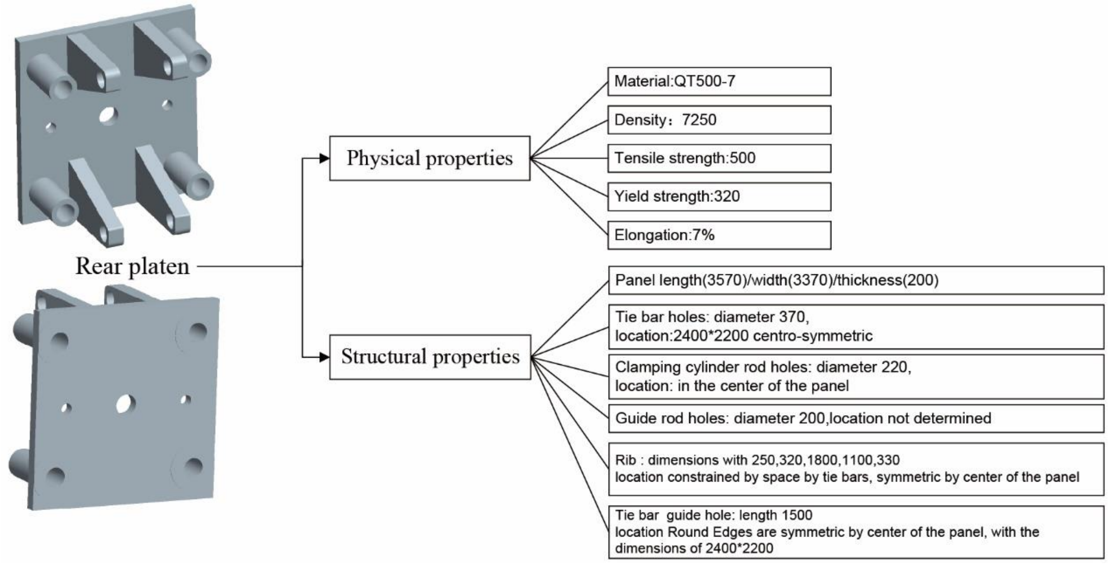

Fig. 13. Rear platen representation model

Table 3. List of design parameters

No.	Name	No.	Name
DP_1	panel length	DP_8	guide rod hole diameter
DP_2	panel width	DP_9	rib length (l_3)
DP_3	panel thickness	DP_{10}	rib thickness (l_2)
DP_4	tie bar hole diameter	DP_{11}	rib short width (l_1)
DP_5	tie bar volume length	DP_{12}	rib long width (l_4)
DP_6	clamping cylinder rod hole diameter	DP_{13}	rib hole diameter (l_5)
DP_7	convex diameter on the panel		

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
DP_1								1	
DP_2								1	
DP_3								1	1
DP_4				1	1				
DP_5				1					
DP_6	1								
DP_7					1				1
DP_8		1							
DP_9								1	
DP_{10}	1								
DP_{11}						1	1		
DP_{12}									
DP_{13}			1						

Fig. 14. Affordance to design parameters matrix of the rear platen

Affordances are perceived for designing the parts which are existing to support specific functions with specific user requirements. So it is necessary to relate the affordances with the requirements. After determining the design specification in section 4.2, user requirements should be determined to make sure that, which kind of customer characteristics may influence the affordances. As the customer requirements are listed in Table 2, designers can achieve the part performance metrics for the rear platen and then construct the performance-to-affordance matrix which is shown in Fig. 15.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
P_1	1		1	1	1				1
P_2								1	
P_3							1	1	

Fig. 15. Performance-to-affordance matrix of the rear platen

The lightweight, high stiffness and high anti-vibration performance items should be determined after the construction of the part model. So in the transmission of conceptual design to detailed design, the three important performance items are laid aside. When the prototype design is finished, these items should be considered as the most important factors.

4.3 Create performance to design parameters model of the rear platen

After creating the ADM and PAM, the steps mentioned above in section 3.4 are used to construct the mapping relations between design parameters and performance metrics for the rear platen. And the DPM is shown in Fig. 16 (the DPM is rotated 90 degrees counterclockwise).

	DP_1	DP_2	DP_3	DP_4	DP_5	DP_6	DP_7	DP_8	DP_9	DP_{10}	DP_{11}	DP_{12}	DP_{13}
P_1	9			4 5	4	1	9 5			1			3
P_2	8	8	8						8				
P_3	8	8	8								7		

Fig. 16 Design parameters-to-performance matrix (DPM) of the rear platen

By the DPM in Fig.16, we can get the relations between the design parameters and the performance items, which in functional forms are:

$$\begin{aligned}
&A_1\ indicates\ P_1 \leftrightarrow (DP_6, DP_9),\\
&A_3\ indicates\ P_1 \leftrightarrow DP_{13},\\
&A_4\ indicates\ P_1 \leftrightarrow (DP_4, DP_5),\\
&A_5\ indicates\ P_1 \leftrightarrow (DP_4, DP_7),\\
&A_7\ indicates\ P_3 \leftrightarrow DP_{11},\\
&A_8\ indicates\ P_2 \leftrightarrow (DP_1, DP_2, DP_3, DP_9),\\
&\qquad\qquad\quad\ P_3 \leftrightarrow (DP_1, DP_2, DP_3),\\
&A_9\ indicates\ P_1 \leftrightarrow (DP_1, DP_7).
\end{aligned} \tag{5}$$

These design parameters represent a set of information that can be used in the original design of a rear platen. Although some affordances relate design parameters to performance items, some affordances which are not appeared in the relation map do not define their uselessness in the design period, where in fact they may be important in the detailed design period. Even if the blanks in Fig. 16 such as DP_8, DP_{12} are not related to the performance items, they are accessory design parameters when the rear platen executes its function in operation of the whole machine.

4.4 construct the rear platen with DPM

When those four steps of the design process are finished, a desired prototype of the rear platen is gotten and can match the customer requirements. The model can be constructed in Fig. 17. With DPM, we first design the tie bar hole and the convex and then the rib. The corresponding design parameters are constrained by the affordances and the performance items. After constructing the connect features of the rear platen, the panel are added to connect them. In order to meet the requirements of stiffness, rigidity and anti-vibration, the rib is added to the constructed model with the confinement from lightweight requirement. At last the rear platen is tested with the FEA tool. The basic modeling process is shown in Fig. 17. The result shows that the model constructed above meets the requirements well in the item of the bearing of huge clamping force despite that it may not be the best scheme for the part. With comprehensive consideration of the gross mass, perfect anti-vibration performance and high rigidity, some multi-optimization methods should be used for detailed design of this rear platen, which will be discussed in the future. Since our model is primitive, lots of optimization are needed to get the optimum model. And the corresponding multi-objective optimization problem for the follow-up design is under proceeding.

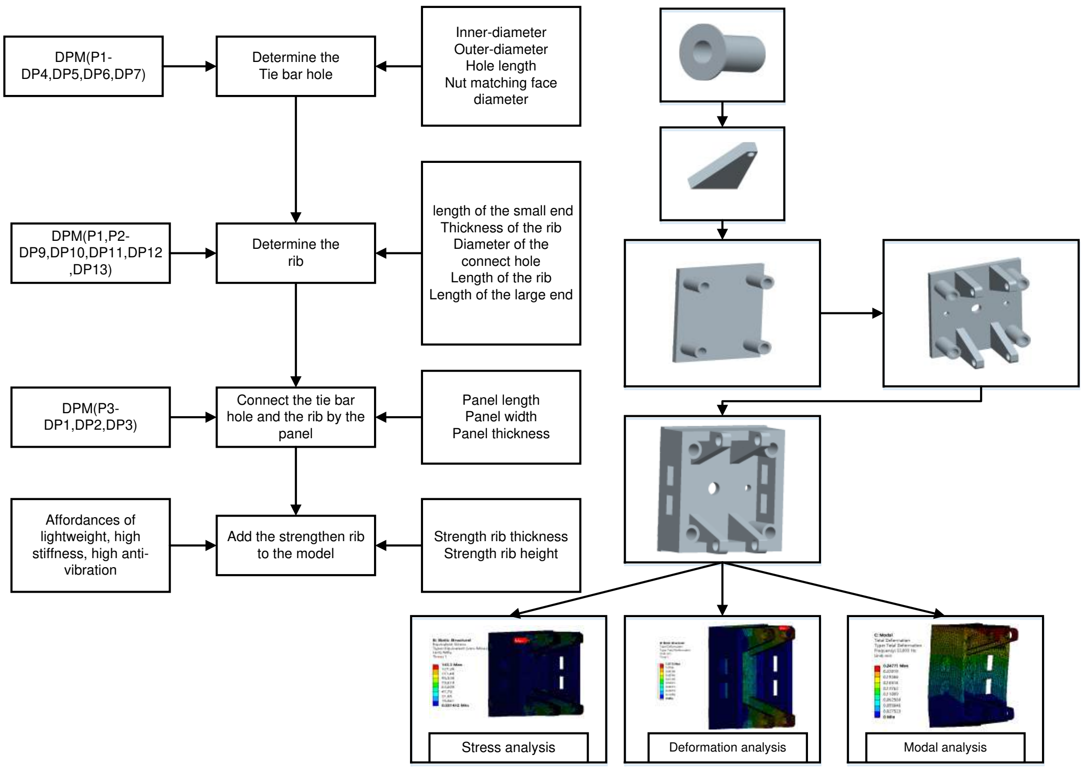

Fig. 17. Design the rear platen with DPM

5 Conclusions

In this paper, an affordance-based design method is proposed for the design of customized non-standard parts, in which a relational specification from design parameter to performance is built by affordances. Thus the impact of user requirements (i.e. performance indexes) on design parameters is clearly achieved and can be used to help designers to make out the part prototype. The liaison graph and the force transmission principle are introduced to identify the affordances among the different parts in the assembly and determine the design priority of the features in the part, respectively.

The DPM is constructed to help designers identify the relation between design parameters and performance items, and affordances are used to assist to identify the design parameters, which compensate the embarrassed situation in which not all of the design parameters are captured by the performance items. A new coarse rear platen of an injection molding machine is designed according to the method proposed above, and the resultant product shows that this method can be feasible and useful in product design.

This method opens a new door for the designers to fulfil the process from conceptual design to detailed design, and that will be in favor of improving the design efficiency and shortening the period of design. For delicate design of the product, there still exist many challenges (e.g. lightweight), this method still need much optimization, and the corresponding investigation is ongoing.

Declarations

1. Availability of data and materials:

Not applicable.

2. Competing interests:

QIU Lemiao, LI Heng, YI Guodong, LIU Xiaojian, ZHANG Peng, ZHANG Shuyou, and TAN Jianrong declare that they have no conflict of interest.

3. Funding:

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4. Authors' contributions:

Authors in this list have contributed equally to this paper.

5. Acknowledgements:

Not applicable.

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Figures

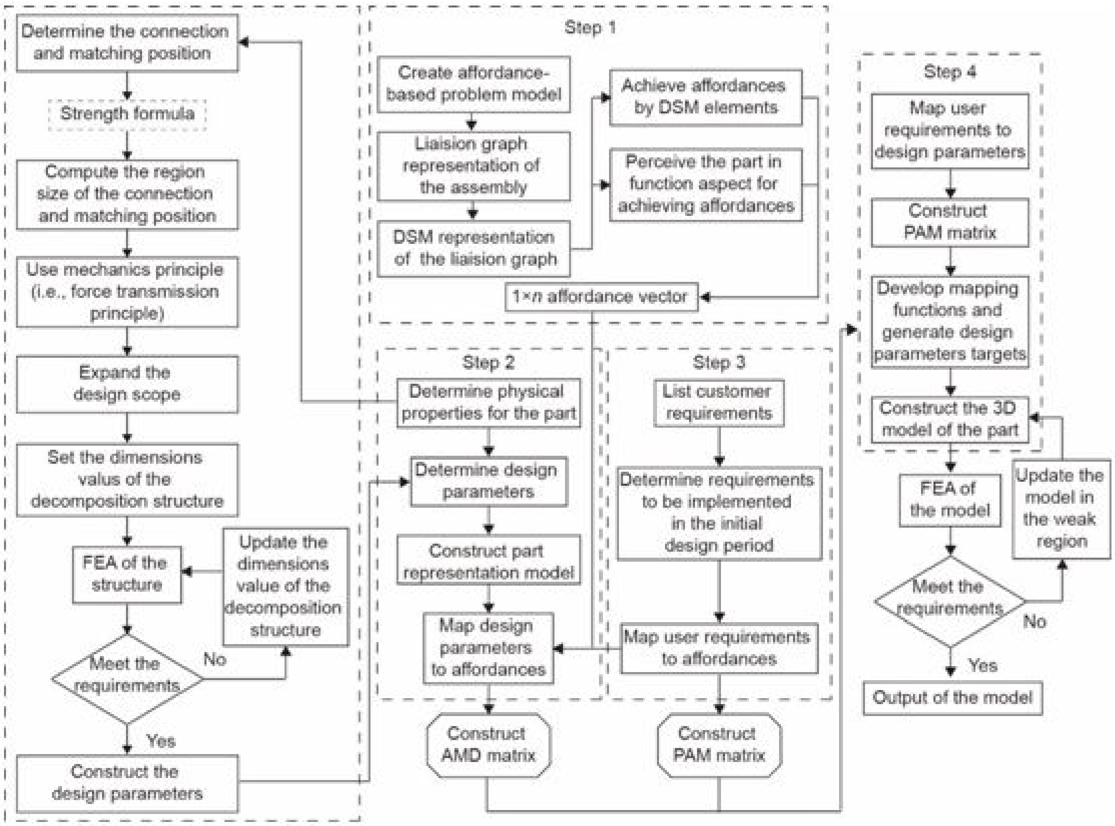


Figure 1

Affordance-based design method flowchart for the non-standard part

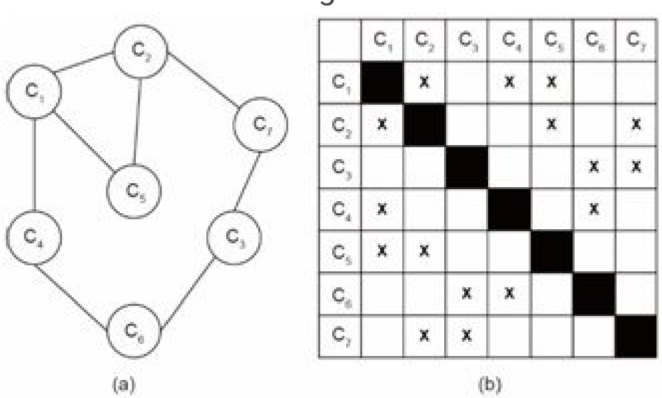


Figure 2

Geometrical relations among the parts:(a) a liaison graph; (b) basic DSM

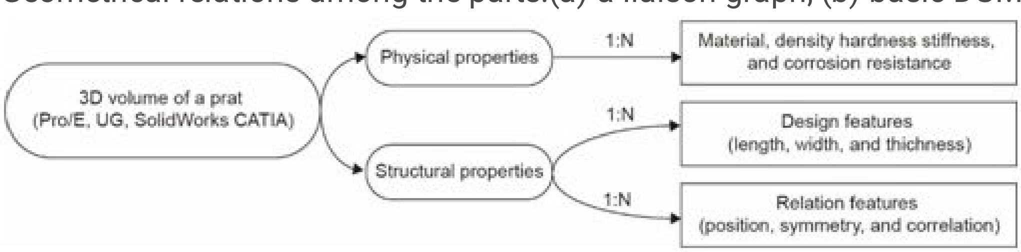
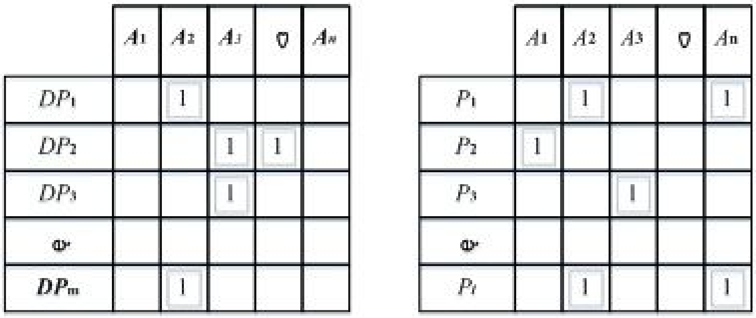


Figure 3

The part representation model

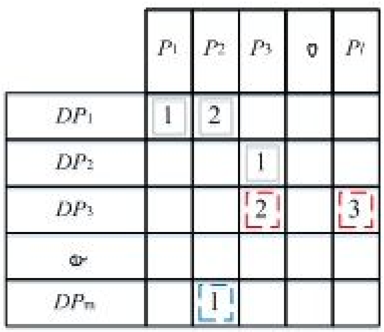


	A_1	A_2	A_3	⋯	A_n
DP_1		1			
DP_2			1	1	
DP_3			1		
⋮					
DP_m		1			

	A_1	A_2	A_3	⋯	A_n
P_1		1			1
P_2	1				
P_3			1		
⋮					
P_l		1			1

Figure 4

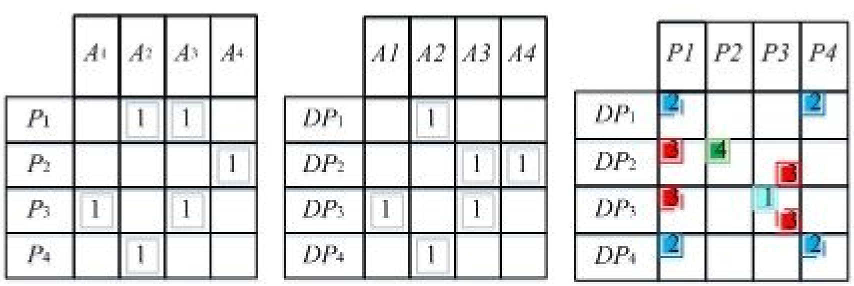
Affordance relation matrix: (a) ADM; (b)PAM



	P_1	P_2	P_3	⋯	P_l
DP_1	1	2			
DP_2			1		
DP_3			2		3
⋮					
DP_m		1			

Figure 5

parameters-to-performance matrix



	A_1	A_2	A_3	A_4
P_1		1	1	
P_2				1
P_3	1		1	
P_4		1		

	$A1$	$A2$	$A3$	$A4$
DP_1		1		
DP_2			1	1
DP_3	1		1	
DP_4		1		

	$P1$	$P2$	$P3$	$P4$
DP_1	2			2
DP_2	3	4	3	
DP_3	3		1 3	
DP_4	2			2

Figure 6

an example of the matrix mapping relation: (a)PAM; (b)ADM; (c) DPM

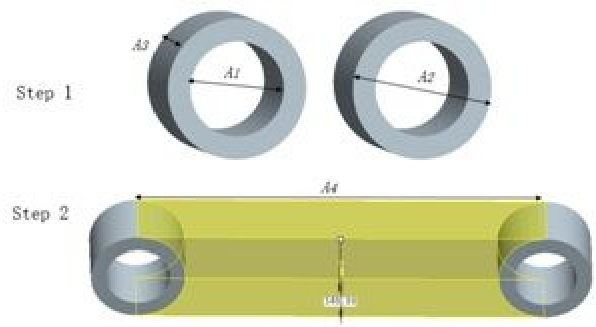


Figure 7

A case for a connect-rod

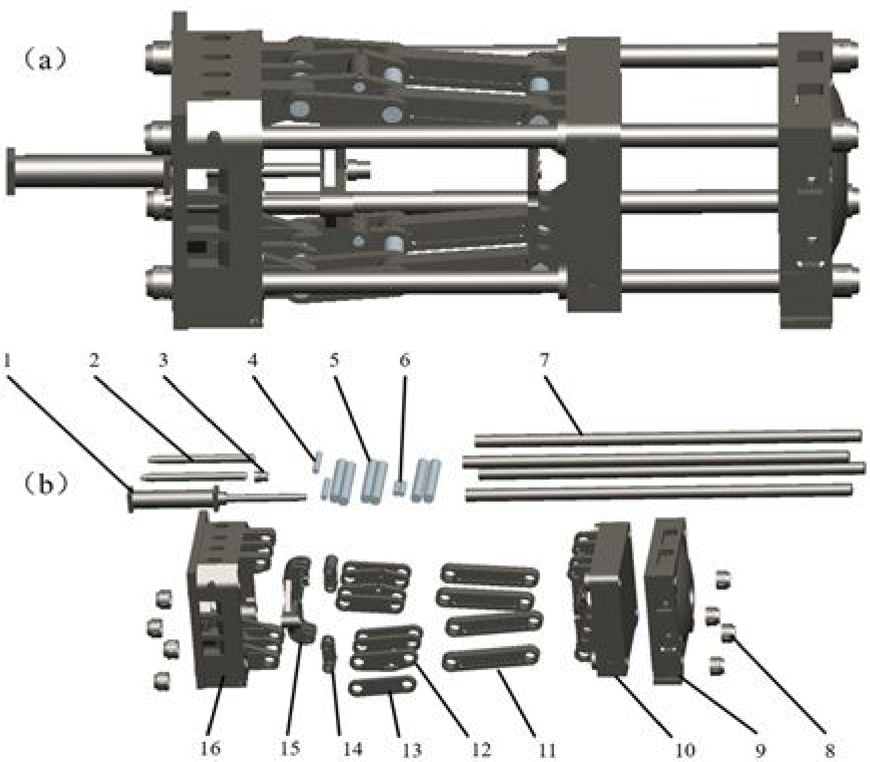


Figure 8

components of the case: (a) the clamping mechanism of an injection molding machine;(b)its explosion modeling in Pro/E

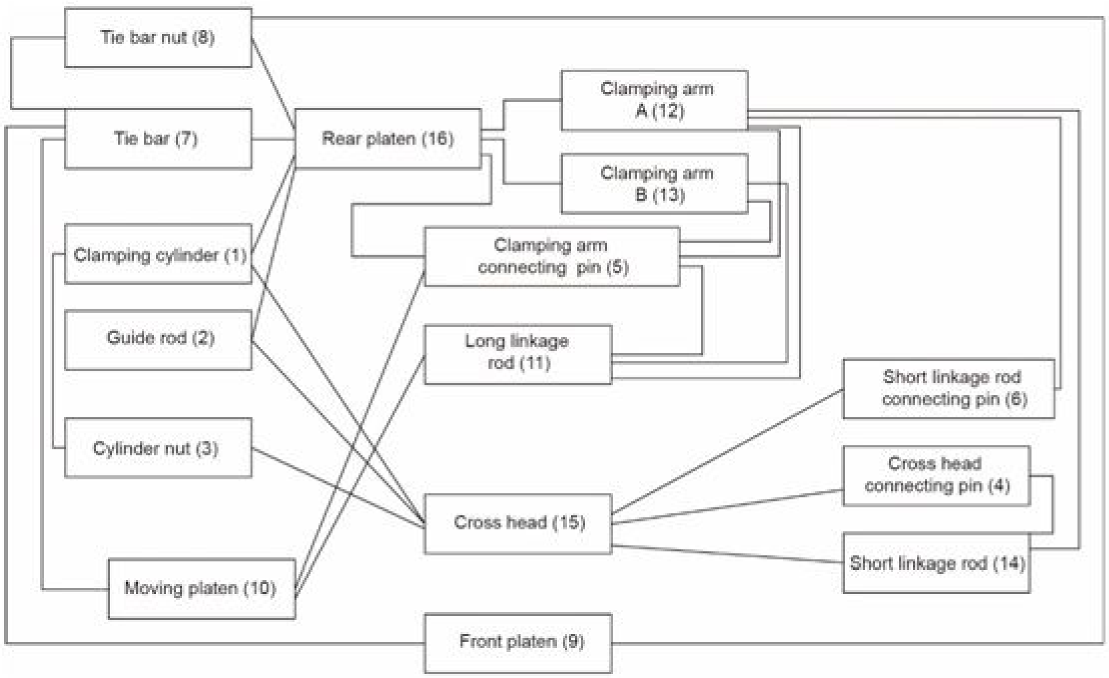


Figure 9

The liaison graph of the clamping mechanism of an injection molding machine

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	■		X												X	X
2		■													X	X
3	X		■												X	
4				■										X	X	
5					■					X	X	X	X			X
6						■						X			X	
7							■	X	X	X						X
8							X	■	X							X
9							X	X	■							
10					X		X			■	X					
11					X						■					
12					X	X					X	■		X		X
13					X								■			X
14				X								X		■	X	
15	X	X	X	X		X								X	■	
16	X	X			X		X	X				X	X			■

Figure 10

Basic DSM of the clamping mechanism

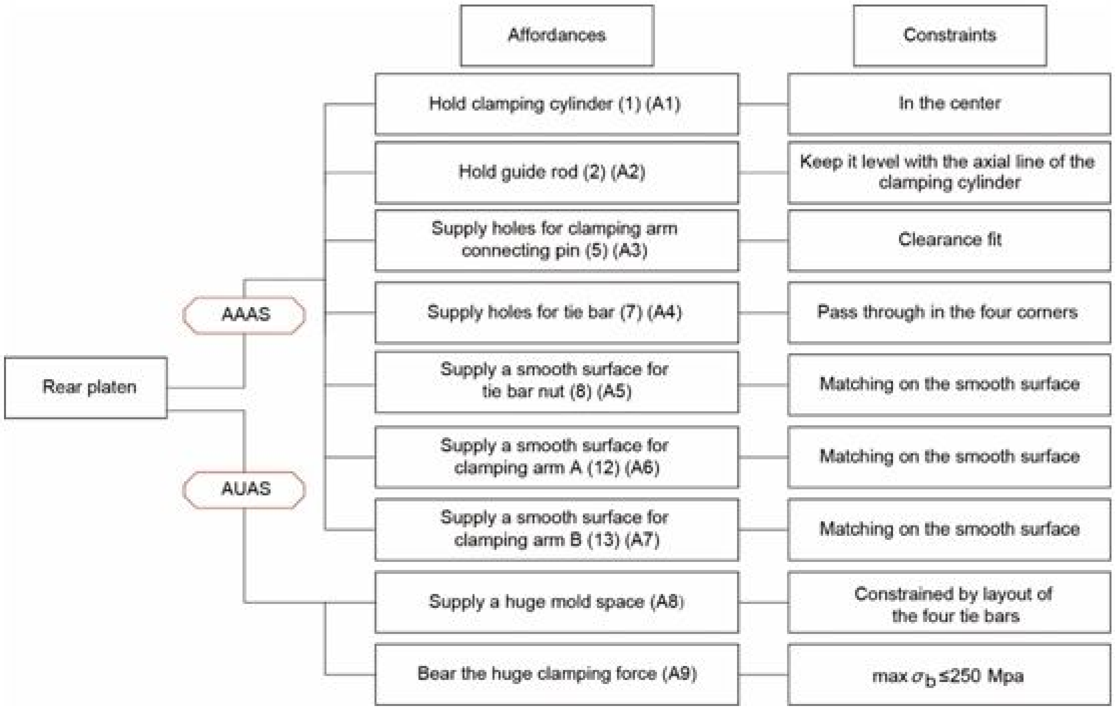


Figure 11

Rear plate n desired affordance model

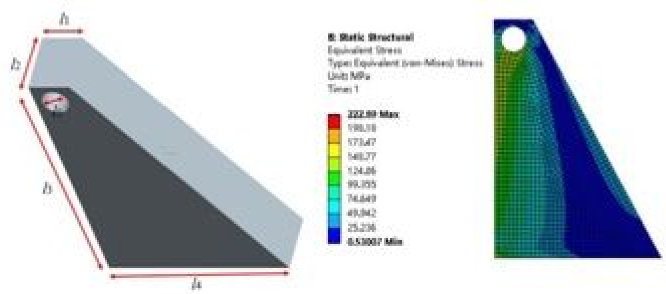


Figure 12

Geometry information and FEM result of the rib

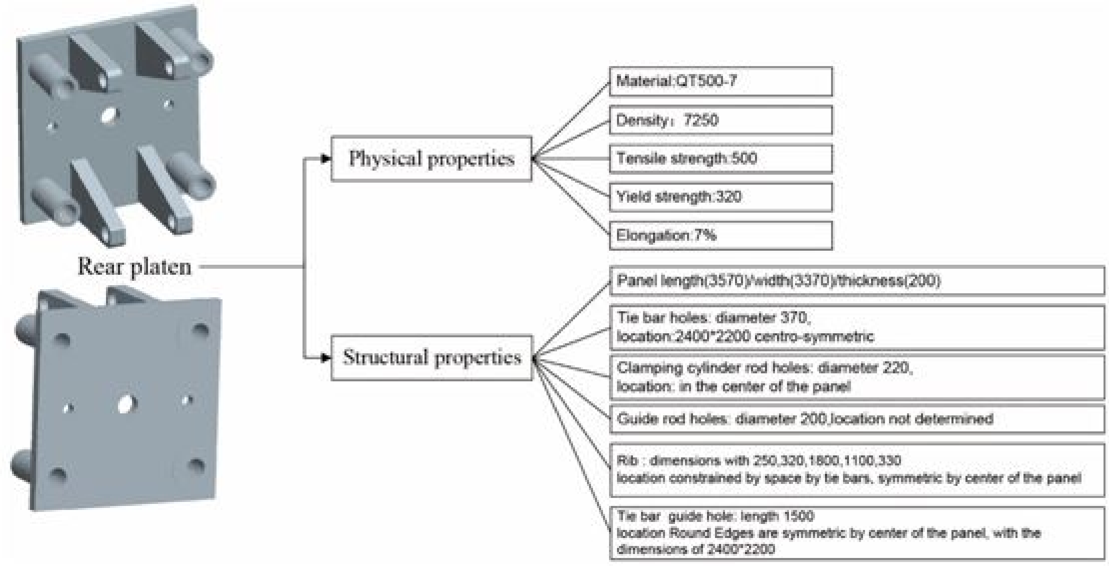


Figure 13

Rear platen representation model

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
DP_1								1	
DP_2								1	
DP_3								1	1
DP_4				1	1				
DP_5				1					
DP_6	1								
DP_7					1				1
DP_8		1							
DP_9								1	
DP_{10}	1								
DP_{11}						1	1		
DP_{12}									
DP_{13}			1						

Figure 14

Affordance to design parameters matrix of the rear platen

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
P_1	1		1	1	1				1
P_2								1	
P_3							1	1	

Figure 15

Performance-to-affordance matrix of the rear platen

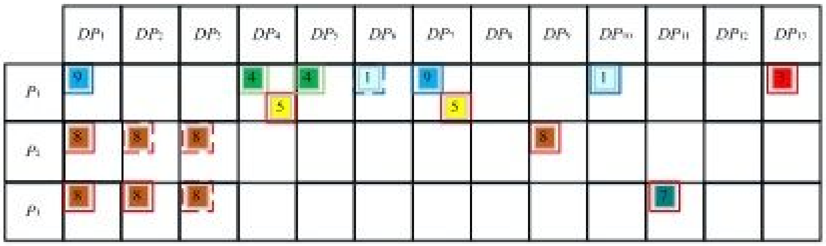


Figure 16

Design parameters-to-performance matrix (DPM) of the rear platen

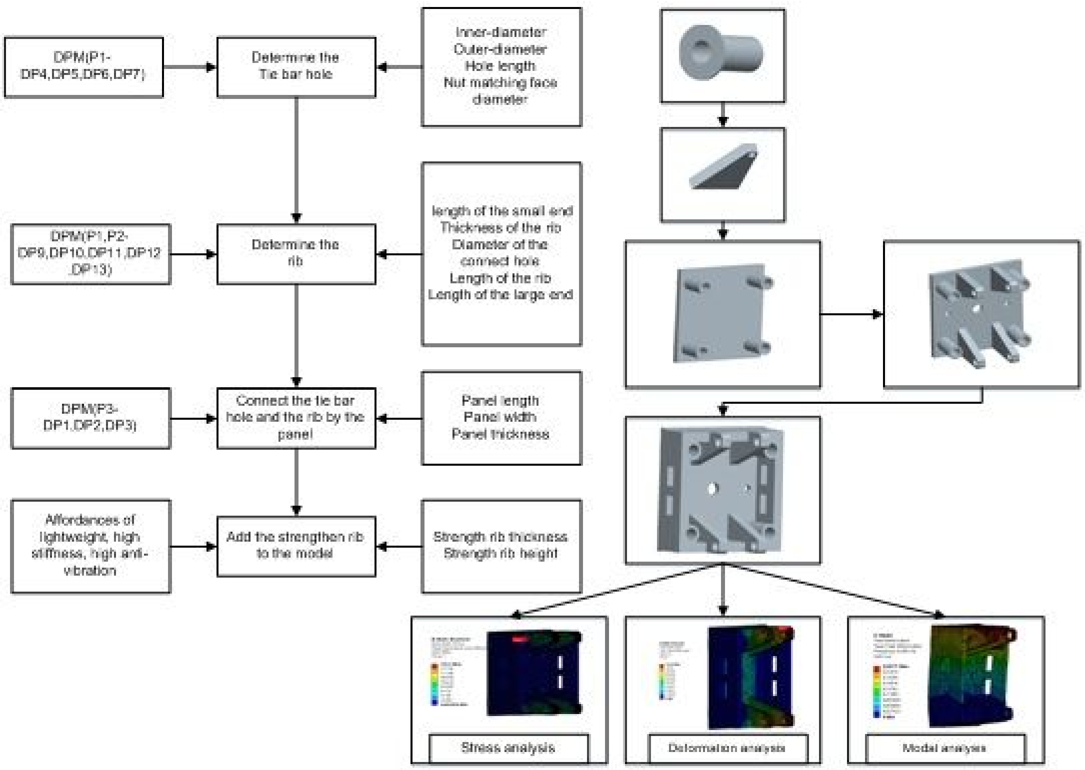


Figure 17

Design there arplaten with DPM