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ORIGINAL ARTICLE

Modular design applied to beverage-container injection molds

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Abstract This work applies modular design concepts to designating beverage-container injection molds. This study aims to develop a method of controlling costs and time in relation to mold development, and also to improve product design. This investigation comprises two parts: functionality coding, and establishing a standard operation procedure, specifically designed for beverage-container injection mold design and manufacturing. First, the injection mold is divided into several modules, each with a specific function. Each module is further divided into several structural units possessing sub-function or sub-sub-function. Next, dimensions and specifications of each unit are standardized and a compatible interface is constructed linking relevant units. This work employs a cup-shaped beverage container to experimentally assess the performance of the modular design approach. The experimental results indicate that the modular design approach to manufacturing injection molds shortens development time by 36% and reduces costs by 19~23% compared with the conventional approach. Meanwhile, the information on modularity helps designers in diverse products design. Additionally, the functionality code helps effectively manage and maintain products and molds.

Keywords Beverage container · Injection mold · Modular design · Product family

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1 Introduction

Recently, growing market competition and increasingly diverse customer demand has forced competitors to increase the speed at which they deliver new products to the market. However, developing a mold for mass production requires considering numerous factors, including product geometry, dimensions, and accuracy, leading to long product development time. Introducing modular design concepts into product design appears a key mean of facilitating product development, since it increases design flexibility and shortens delivery time [1–4]. Meanwhile, a high level of product modularity enhances product innovativeness, flexibility, and customer services [5].

Modularity is to subdivide a complex product into modules that can be independently created and then are easily used interchangeably [6, 7]. There are three general fields where modularity could be implemented including modularity in design (MID), modularity in use (MIU), and modularity in production (MIP) [8]. MID involves standardizing basic structural units which perform specific functions, thus facilitating flexible assembly of various products [9, 10]. MID can reveal product structure, namely the relationship among different products. Related products are termed product family and include both basic and specific functions. Developing product families offers benefits in terms of multi-purpose design and thus reduces production costs [11, 12]. MIU is consumer-driven decomposition of a product with a view to satisfying the ease of use and individually. MIP enables the factory floor to precombine a large number of components into modules and these modules to be assembled off-line and then brought onto the main assembly line to be incorporated into a small and simple series of tasks.

MID has been broadly applied to numerous areas and has exerted significant effects in terms of cost reduction and design diversity [13, 14]. However, there is limited empirical research that has applied modular design to molds [15–18]. This study thus aims to reduce mold development time by applying modular design and develop a standard operation procedure for designing beverage-container injection molds, which are characterized by scores or even hundreds of components.

2 General procedures of designing injection molds

Basically, an injection mold set consists of two primary components, the female mold and the male mold. The molten plastic enters the cavity through a sprue in the female mold. The sprue directs the molten plastic flowing through runners and entering gates and into the cavity geometry to form the desired part. Sides of the part that appear parallel with the direction of the mold opening are typically angled slightly to ease rejection of the part from the mold. The draft angle required for mold release is primarily dependent on the depth of the cavity and the shrinkage rate of plastic materials. The mold is usually designed so that the molded part reliably remains on the male mold when it opens. Ejector pins or ejector plate is placed in either half of the mold, which pushes the finished molded product or runner system out of a mold. The standard method of cooling is passing a coolant through a series of holes drilled through the mold plates and connected by hoses to form a continuous pathway. The coolant absorbs heat from the mold and keeps the mold at a proper temperature to solidify the plastic at the most efficient rate. To ease maintenance and venting, cavities and cores are divided into pieces, called inserts. By substituting interchangeable inserts, one mold may make several variations of the same part.

General mold design process contains two parts [19]: part design and mold design. The part design process contains five major procedures: defining main pulling direction, defining core and cavity, calculating shrinkage rate, defining draft angle, and then defining parting line. The mold design process mainly includes choosing a mold base, positioning the molded part, designing core and cavity, designing components, designing coolant channels, creating returning pin, adding ejector pin, creating gate and runner, adding locating ring and sprue bushing in sequence.

3 Applying modular design for beverage containers

This study applies modular design to beverage-container injection molds via a five stage process, as follows: (1) product classification and machine specifications, (2) division of injection molds into modules based on functionality, (3) division of individual modules into multiple units with sub-functions, and the relationship between design and assembly for each unit, (4) standardization of structural units, and (5) coding of standard structural units. These individual processes are detailed below.

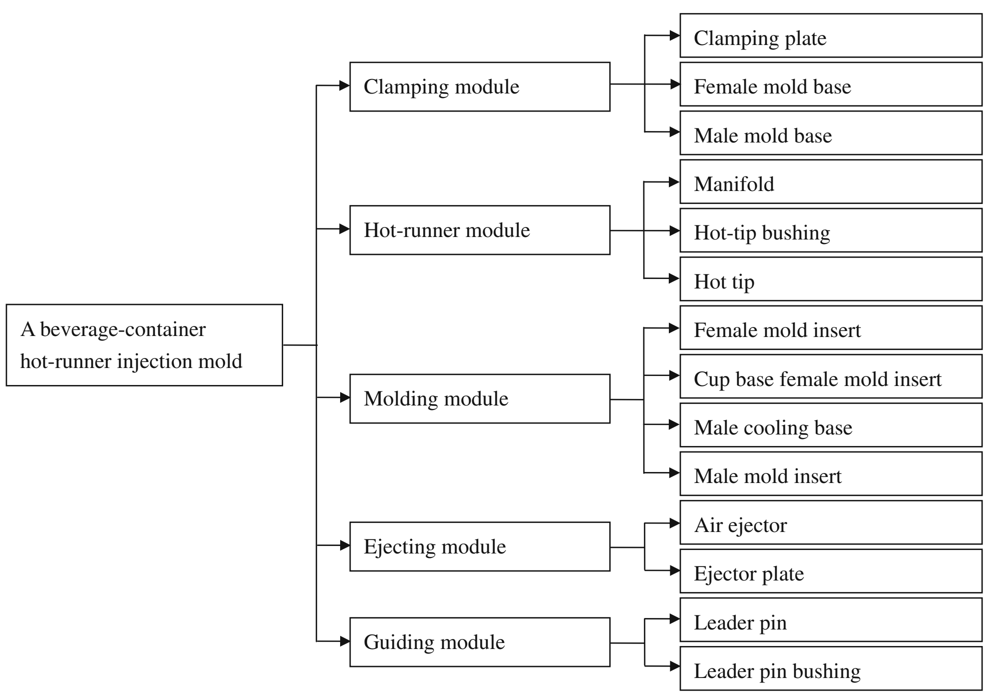


Fig. 1 Modularity classification of a beverage-container injection mold

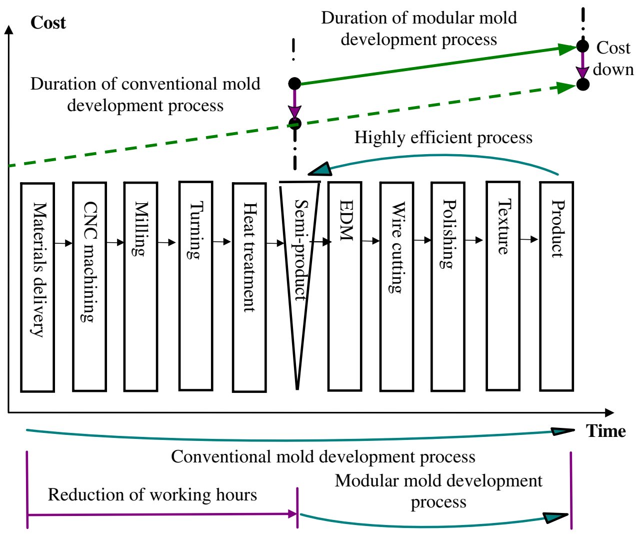


Fig. 2 Comparison of conventional and modular mold development processes

3.1 Product classification and machine specifications

This step classifies all of the beverage containers based on their geometry and dimensions, and selects the machine with the most suitable specifications for production. There are five major qualifications for an injection molding machine, including sufficient mold clamping force, sufficient theoretical shot volume, sufficient distance between tie bars, sufficient range of mold thickness, and sufficient mold clamping stroke.

3.2 Division of injection molds into modules based on functionality

This step divides a mold set into several modules with individual functions. The principles of division include general rule, division rule, applicability rule, and interchange rule. In general rule, modules must contain all the functions of beverage-container injection molds. In division rule, each functional module must contain at least one fundamental function and each unit must fulfill its own specific functions. As to applicability rule, units fulfilling a single function are preferred. For interchange rule, fundamental units should be interchangeable among modules after dividing molds into product families.

3.3 Division of a module into multiple units with sub-function and the relationship between design and assembly for each unit

Figure 1 illustrates the structure of a beverage-container mold that includes several functional modules. The functions of individual modules are further extended to the structural unit via sub-functions or sub-sub-functions. The divided modules include clamping module, hot-runner module, molding module, ejecting module, and guiding module. The clamping module functions for precisely positioning individual units and modules on an injection molding machine. The hot-runner module is to maintain the flowability of molten plastics via heating. The molding

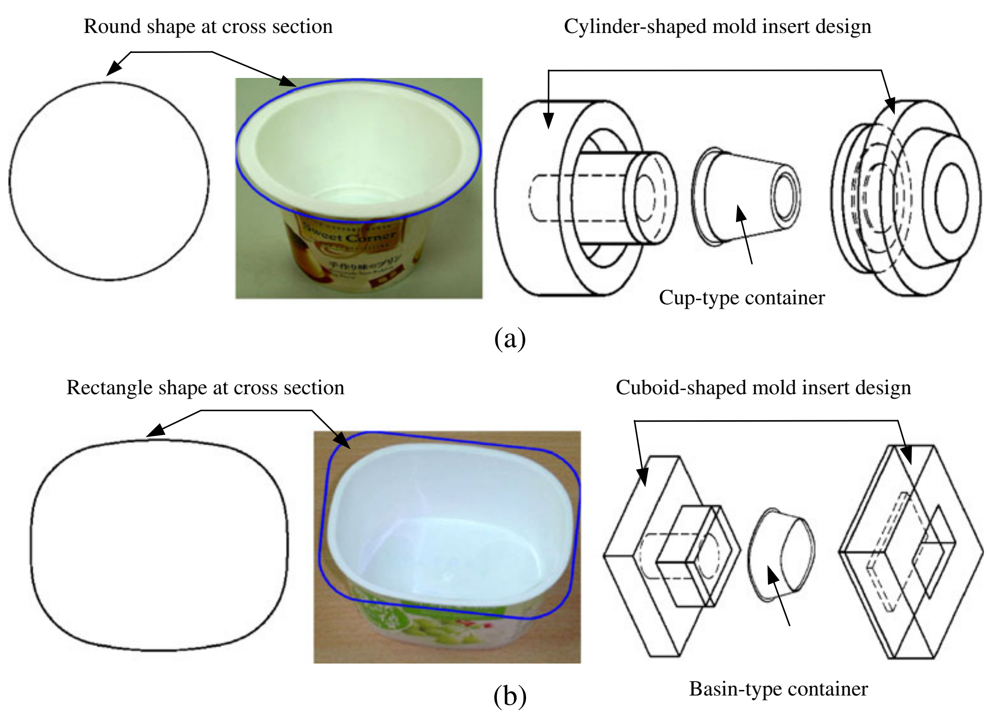


Fig. 3 Design of geometrical structural unit: **a** cup-type container, **b** basin-type container

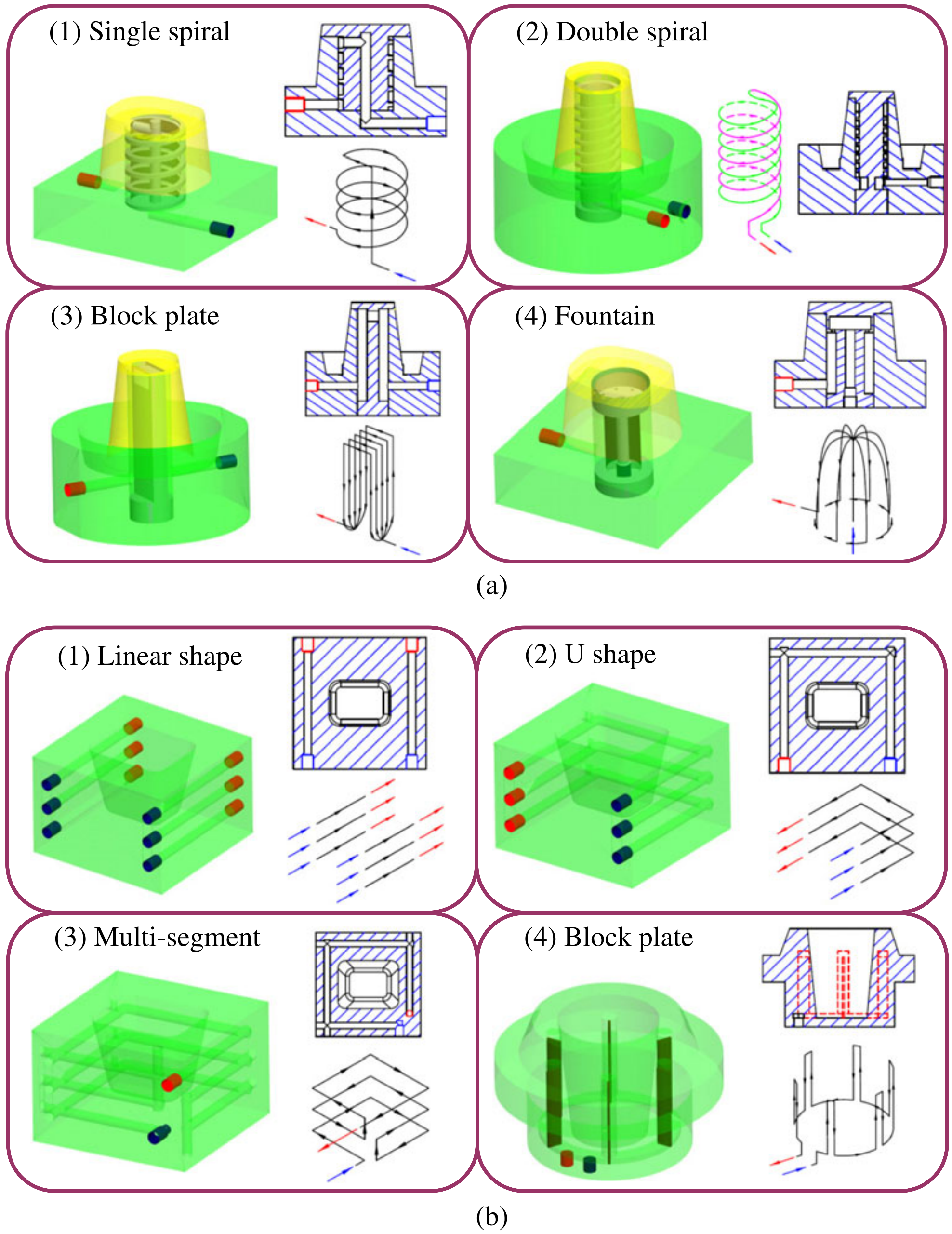


Fig. 4 Design of cooling system: **a** the male portion of the mold cooling unit, **b** the female portion of the mold cooling unit

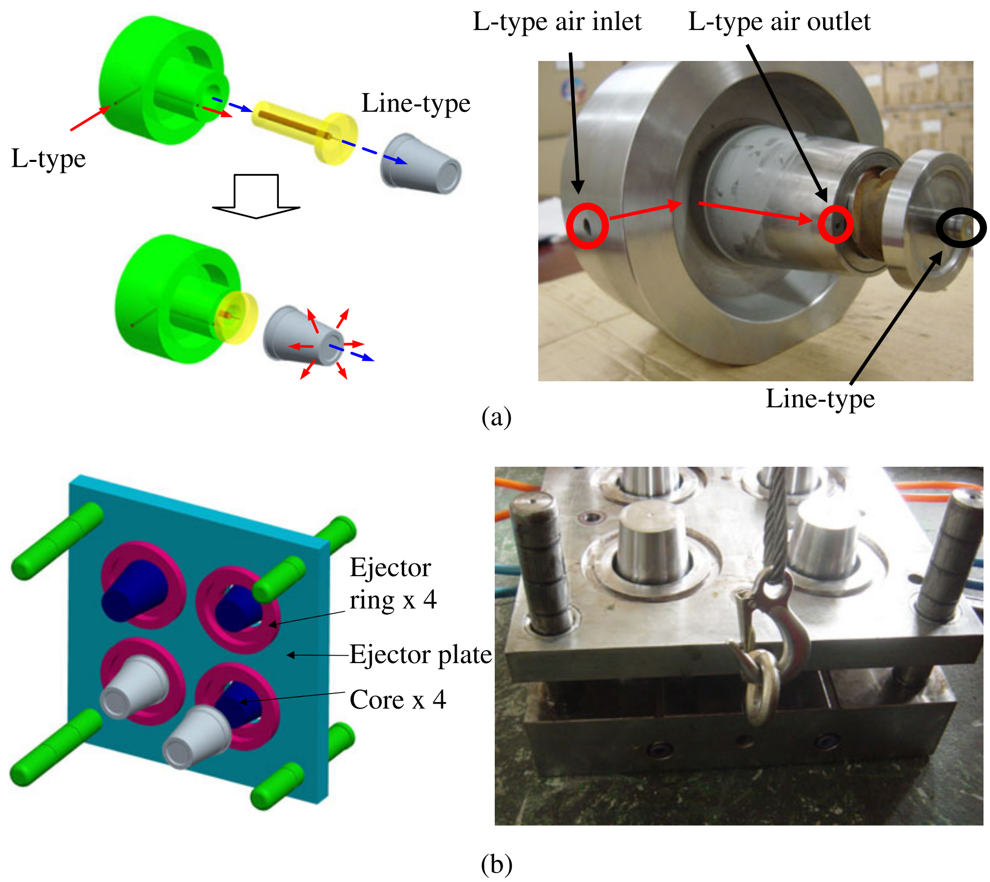
module controls the geometry and dimensional accuracy of injection-molded parts. The ejecting module ejects injection-molded parts from the mold cavity. The guiding module works for accurately positioning the female and male molds during mold closing.

3.3.1 Geometrical design of structural elements

Standard structural elements are prepared into semi-finished products that fulfill the geometrical outlines of finished products, thus significantly shortening manufacturing mold delivery time. Figure 2 illustrates the comparison between the modularity design mold development process and the conventional process. Standard structural elements are fast to produce since they are pre-manufactured into general shapes and require minimal manufacturing to yield a finished product.

Figure 3 shows the geometrical design of the beverage containers examined in this study. The mold insert that best correspondents with the product shape has a simple geometrical shape. For example, the cylinder and the cuboid represent cup-type and basin-type containers, respectively. The remaining components are modularized to facilitate their effective integration into a complete set of injection molds in a manner similar to stacking playing blocks.

Fig. 5 Design of ejector: **a** air ejector, **b** ejector plate



3.3.2 Assembly design of structural unit

Hundreds of structural elements are involved in new product development, each containing numerous dimensions. Assembling such a sophisticated system may frequently fail because of small mistakes occurring in dimensions. This study defines dimensions involving structural elements with mutual assembly relationships as union dimensions. These dimensions are simplified to a fool-proofing effect. Procedures for assembling structural elements are introduced below:

(1) Direction of module assembly—Two lines are used to separate a mold into four assembly modules. The first line is the parting line defining the female and male molds. The second line defines the boundary between the front and rear hot-runner plates. The sequence of assembly follows the order of male mold, female mold, front hot-runner plate, and rear hot-runner plate.
(2) Direction of assembly units—Each unit belonging to the above-mentioned four assembling modules is assembled in a sequence, namely, confirming the appearance dimensions of injection-molded parts, further confirming the product-related dimensions of the mold insert and mold cavity, fixing the mold insert with the clamping module, identifying the dimension of the hot-runner module using the structural components of the female mold, calculating the precise dimensions of the clamping plates, and finally selecting the injection molding machine specifications. The assembling sequence primarily follows product, mold insert, clamping plate, and injection molding machine.

3.4 Standardization of structural unit

As for the structural units of beverage-container injection molds, the concept of product families is further introduced to increase the commonality and exchangeability among various functional units. Figure 4 illustrates an example of mutually substitutable cooling systems. Furthermore, Fig. 5 shows the design of various ejection systems used for product families.

3.4.1 Design of cooling system

The cooling system comprises two units: male mold cooling unit and female mold cooling unit. The male mold cooling unit includes fountain, double spiral, single spiral,

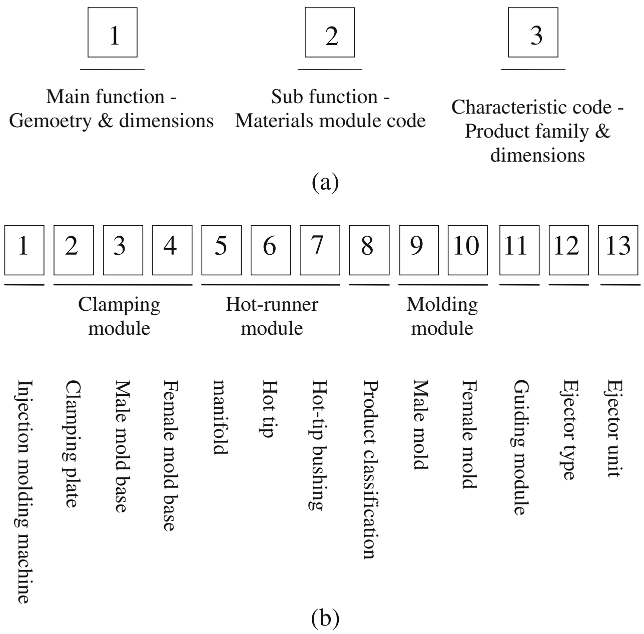


Fig. 6 Code of modular functionality: **a** structural unit codes, **b** product identification complex code

and block plate types listed in descending sequence of cooling efficiency. Based on manufacturing cost and cooling effect, the double spiral type is prioritized. As to the female mold cooling unit, it includes multi-segment, block plate, U shape, and linear types listed in descending sequence of cooling efficiency. Based on manufacturing cost and cooling effect, block plate is prioritized.

3.4.2 Design of ejection mechanism

The beverage container is normally thin-walled and the ideal ejection mechanism is an air ejector, based on the desirability of preventing damage to injection-molded parts. As for injection molding materials with high shrinkage, the ejector plate can be selected to smoothly separate the products and mold. The air ejector design incorporates two air outlets around the mold insert, namely, one L-type outlet and one line-type outlet. The air in the L-type outlet enters the periphery of the mold insert and separates the injection-molded parts from the mold insert. The air in the line-type outlet is then injected into the bottom of the parts to eject them from the mold cavity. Ejector plate is to push a molded part off a core or out of a cavity mold. It is attached to a core and moves linearly along leaders.

3.5 Coding of standard structural units

After specifying structural unit dimensions, this investigation introduces a coding system to assist in managing these components and units.

3.5.1 Structural unit codes

This study uses three digits to code all of the structural units (Fig. 6a). The first digit is the main function code, which represents product geometry and dimensions, and symbolizes standardized structural units. The second digit is the sub-function code, which represents materials, and is widely used in bills of materials (BOM) for structural units. The third digit represents the characteristics of each structural unit, and includes the codes for products families and dimensions.

3.5.2 Product identification complex code

This code is designed for rapidly searching structural units which are mutually exchangeable during product development. This code integrates all structural units correlated with the manufacture of a specific container, and also reveals information on mold geometry and dimensions, and product characteristics, as shown in Fig. 6b.

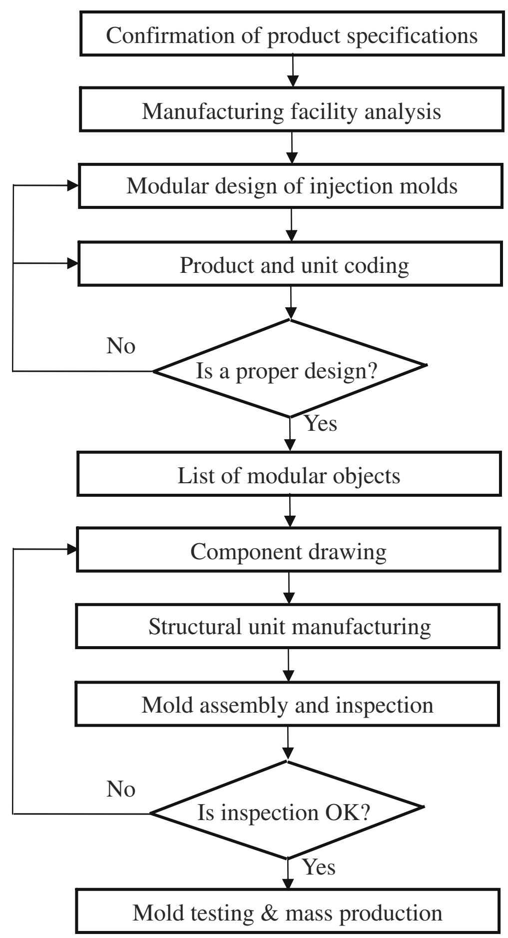


Fig. 7 Standard operation procedure for developing beverage-container injection molds

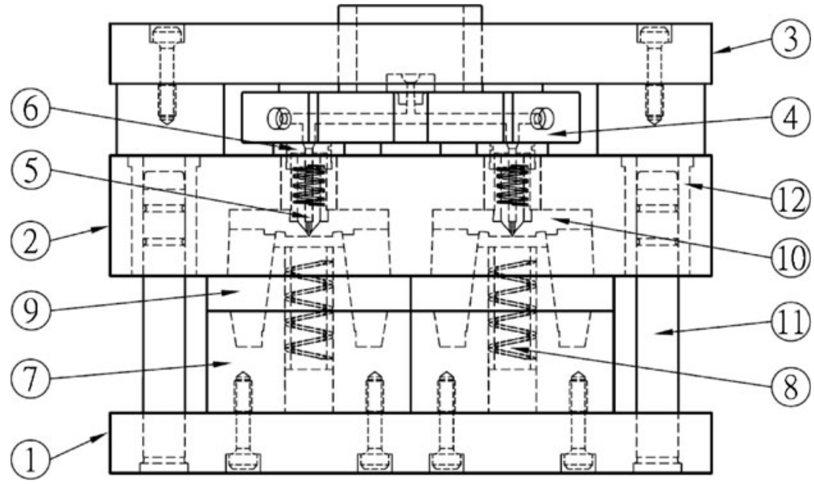


Fig. 8 BOM of a cup-shaped injection mold

No.	Title	Code	Specifications	Materials	Amount	Auxiliary
1	Cup-shaped male mold base	6-2-N	L450 × H450 × T60	S55C	1	Heat treatment
2	Cup-shaped female mold base	19-2-N	L450 × H450 × T130	S55C	1	Heat treatment
3	Clamping plate	3-2-N	L450 × T50 ×ψ120	S55C	1	-
4	Manifold	4-2-N	L330 × H90 × T43	SKD61	1	-
5	Hot tip	2-1-N	ψ14 × L90	Beryllium Copper	4	-
6	Hot-tip bushings	2-3-N	ψ20 × L60	FDAC	4	-
7	Cup-shaped male mold insert	19-1-N	ψ150 × H130	SUS420	4	-
8	Cooling unit of male mold	19-2-T	ψ90 × H130	SDK11	4	Heat treatment
9	Cup-shaped base female mold insert	19-1-N	ψ150 × H110	SUS420	4	-
10	Cup-shaped female mold insert	19-2-N	ψ130 × H20	SKD11	4	Heat treatment
11	Leader pin	6-1-15	ψ40 × L260	SK3	4	-
12	Leader pin bushing	6-1-21	ψ55 × L100	SK3	4	-

4 Procedure for developing container products

Based on the above-mentioned modular design approach, a standard operation procedure for designing beverage-container injection molds can be generated. Thus, merely following the procedure can easily design molds for new products and identify interchangeable structural units which can help effectively manage and maintain products and molds. Figure 7 shows the standard operation procedure for designing beverage-container injection molds. The procedure comprises nine steps and is illustrated as follows.

Step 1. Confirmation of product specifications: In order to exactly describe the geometry, dimensional accuracy, and quality characteristics of products, this step defines the product with its geometrical characteristics, such as width, height, projection area, and weight.

Step 2. Manufacturing facility analysis: Based on the information from Step 1, the most suitable injection molding machine is determined by checking specifications such as clamping force, shot volume, range of mold thickness, and daylight.

Step 3. Modular design of injection molds: Through the division of mold function into several functional modules, the injection mold of a specific container can be rapidly and easily developed by module stacking. Modules to be designed include male mold module, female mold module, hot-runner module, and others.

Step 4. Product and unit coding: Each structural unit is assigned a component code, which is then integrated with the product characteristics to yield a product complex identification code. Consequently, mutually exchangeable units are available in the product development stage. Furthermore, the code system simplifies mold maintenance and product management.

Step 5. List of modular objects: According to the structural specifications from Step 3, all components of an injection mold are listed in BOM. For instance, the BOM of a cup-shaped injection mold as an example is illustrated in Fig. 8. This step facilitates ease of handling during the subsequent quotation and production scheduling process.

Step 6. Component drawing: Since dimensions of structural units are for semi-products, the BOM information listed in Step 5 simply is the initial stage of mold design. Thereby, all structural units of an injection mold designed for customer requirement and specification have to be drawn in the format of engineering drawing for engineering purposes.

Step 7. Structural unit manufacturing: Following the information of BOM and component drawing generated in Steps 5 and 6, respectively, this step enables the factory floor to further manufacture the injection mold.

Step 8. Mold assembly and inspection: This step inspects each unit manufactured in Step 7 to assure mold quality. Based on the assembly drawing of a mold, the location of related modules and structural units is accurately assembled. For instance, Fig. 9 presents the assembly drawing of a coffee-cup injection mold, which is used to confirm the relationship of each component.

Step 9. Mold testing and mass production: After completing the above eight steps, this final step is performed to test the mold on the injection molding machine and implement mass production.

5 Verification and discussion

This study employs a cup-shaped beverage container to experimentally assess the performance of the modular design approach. Since the specification of structural units enables preprocessing of the initial unit shape and only requires local preprocessing to obtain precise dimensions during mold development, the total mold development time will be significantly reduced. Table 1 lists mold development for a cup-shaped container and reveals that the mold development time employing a modular design is some 36% less than with the conventional process. Whereas the standardization of component specifications enabling batch purchasing of materials which are combined with efficient manufacturing and design, can reduce total manufacturing costs. Table 2 lists mold development for a cup-shaped container and reveals that mold manufacturing costs when employing a modular design are reduced by 19~23% compared with the conventional process. In addition, employing modular design has other advantages such as:

1. Increased diversity of customer-oriented design: Modular design of beverage-container injection molds involves dividing a mold into five key functional modules and 14 sub-functional structural units. A mutually compatible interface among units is created via the specification and standardization of individual structural units. Moreover, product families with various function structures containing different types of cooling effects in mold insert cooling unit and different types of ejecting effects in the injection unit are defined. Each unit type is substitutable, facilitating product assembly and disassembly, enhancing design flexibility, increasing producer ability to adapt to market variation, and fulfilling various types of customer demand.

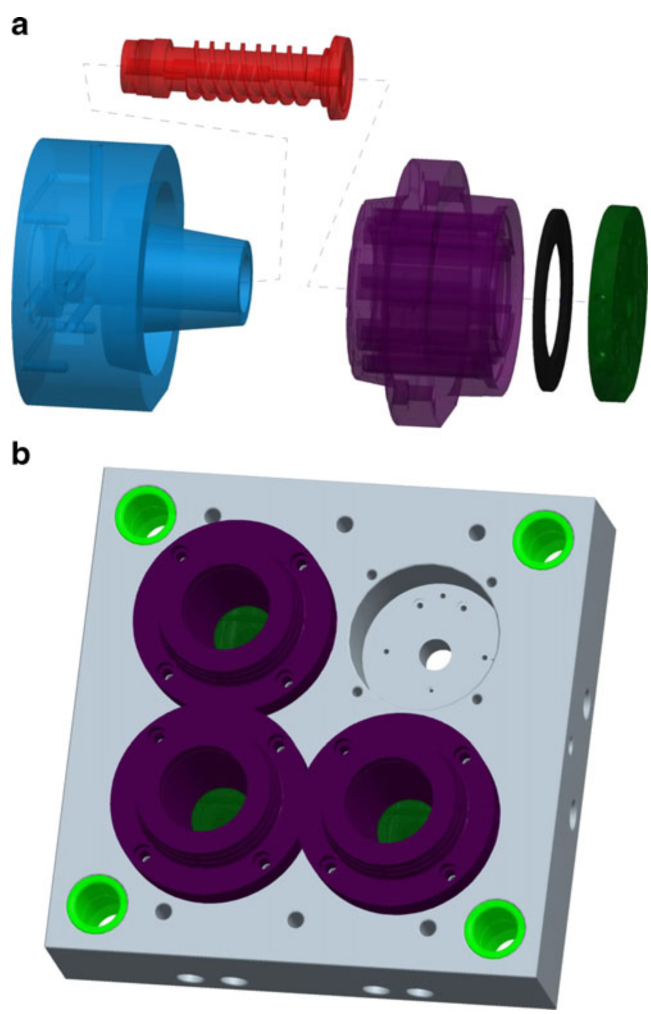


Fig. 9 The assembly drawings of a coffee-cup injection mold: **a** mold insert, **b** female mold base

Table 1 List of manufacturing time savings for a cup-shaped container

Structural unit	Conventional mold manufacturing time (h)	Modular mold manufacturing time (h)	Saving of modular mold manufacturing time (h)	Percentage of modular mold manufacturing time (%)
Clamping plate	8	6	2	25
Manifold	38	26	12	32
Hot-tip bushing	6	5	1	17
Hot tip	4	3	1	25
Female mold base	40	29	11	27
Female mold insert	52	16.5	35.5	69
Cup-base mold insert	49.5	43	6.5	13
Cooling unit of male mold	44.5	38	6.5	15
Male mold insert	56	24	32	57
Male mold base	8	6	2	25
Summary	306	196.5	109.5	36

2. Information provision to facilitate rapid product development: The use of coding system for standard functional modules and structural units enables the construction of a standard product development procedure. This procedure enables designers to quickly follow correct design steps and to further complete detailed injection mold design.
3. Effective management of the maintenance of products and molds: The developed coding system enables rapid response to repair inquiries by providing available components that are mutually replaceable from among units held in stock. Furthermore, structural units of a product and information on product characteristics are coded using a specialized individual identification number to facilitate new product development.

6 Conclusions

This study applied modular design theory and principles in developing beverage-container injection molds. The standard operating procedure for developing mutually substitutable standard component mold designs has been demonstrated. This work only presents a single cup-shape and basin-shape container injection mold as a research vehicle for modular design, and yields valid results in terms of saving time and reducing manufacturing costs. Based on the database of standard structural units constructed for beverage containers, the application of computer-aided design and computer-aided manufacturing can reveal the effect of modular design. Practical case studies indicate that the proposed procedure enables the design of standard

Table 2 List of cost savings for a cup-shaped container

Structural unit	Materials discount at batch purchasing (%)	Reduction at manufacturing time (%)	Reduction in designing and other cost (%)	Cost saving among modular units (%)
Clamping plate	0.15~0.44	0.57	0.13~0.26	0.85~1.27
Manifold	0.10~0.31	0.62	0.13~0.26	0.85~1.19
Hot-tip bushing	0.03~0.09	0.10	0.13~0.27	0.26~0.46
Hot tip	0.02~0.05	0.12	0.13~0.27	0.27~0.44
Female mold base	0.28~0.83	2.98	0.15~0.29	3.41~4.11
Female mold insert	0.17~0.50	4.53	0.16~0.32	4.86~5.36
Cup-base mold insert	0.06~0.17	0.24	0.16~0.31	0.46~0.73
Cooling unit of male mold	0.09~0.28	0.38	0.16~0.31	0.63~0.97
Male mold insert	0.20~0.06	5.64	0.16~0.32	6.00~6.56
Male mold base	0.17~0.52	1.28	0.14~0.28	1.59~2.09
Summary	1.27~3.80	16.46	1.46~2.92	19.19~23.18

components for various products and thus can considerably reduce working hours and costs. Thereby the proposed approach is feasible in beverage-container mold design and is also applicable to other injection molds. For long-term mold development, the economic efficiency of batch purchasing owing to using common units for product families should be valuable.

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