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Intelligent Conceptual Mould Layout Design System (ICMLDS)

Innovation Report

By

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(Intake date: 1st October 2007)

Sponsored by

Luen Shing Tools Limited

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for the degree of Doctor of Engineering at the

University of Warwick

March 2012

DECLARATIONS

I hereby declare that I am the sole author of this Innovation Report.

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Ivan Chan. **21 March 2012**

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ABSTRACT

Family Mould Cavity Runner Layout Design (FMCRLD) is the most demanding and critical task in the early Conceptual Mould Layout Design (CMLD) phase. Traditional experience-dependent manual FCMRLD workflow results in long design lead time, non-optimum designs and costs of errors. However, no previous research, existing commercial software packages or patented technologies can support FMCRLD automation and optimisation. The nature of FMCRLD is non-repetitive and generative. The complexity of FMCRLD optimisation involves solving a complex two-level combinatorial layout design optimisation problem. This research first developed the Intelligent Conceptual Mould Layout Design System (ICMLDS) prototype based on the innovative nature-inspired evolutionary FCMRLD approach for FMCRLD automation and optimisation using Genetic Algorithm (GA) and Shape Grammar (SG). The ICMLDS prototype has been proven to be a powerful intelligent design tool as well as an interactive design-training tool that can encourage and accelerate mould designers' design alternative exploration, exploitation and optimisation for better design in less time. This previously unavailable capability enables the supporting company not only to innovate the existing traditional mould making business but also to explore new business opportunities in the high-value low-volume market (such as telecommunication, consumer electronic and medical devices) of high precision injection moulding parts. On the other hand, the innovation of this research also provides a deeper insight into the art of evolutionary design and expands research opportunities in the evolutionary design approach into a wide variety of new application areas including hot runner layout design, ejector layout design, cooling layout design and architectural space layout design.

PUBLICATIONS ARISING FROM THIS RESEARCH

This research involves four publications. They are listed below:

(i) Ivan W.M. Chan, Martyn Pinfold, C.K. Kwong and W.H. Szeto, (2011), "A review of research, commercial software packages and patents on family mould layout design automation and optimisation", *International Journal of Advanced Manufacturing Technology, Vol.* 57, pp. 23-47, DOI 10.1007/s00170-011-3268-8

(ii) Ivan W.M. Chan, Luen Shing Tools Limited, (2011), "An intelligent evolutionary design method and system for family mould layout design automation and optimisation", Provisional application for the United States Patent (Application No. 61560294, Filing date: 16 November 2011)

(iii) Ivan W.M. Chan, Martyn Pinfold, C.K. Kwong and W.H. Szeto, (2011), "Shape grammars for generative family mould cavity and runner layout design", *International Journal of Production Research* (planned to be submitted after the patent is granted)

(iv) Ivan W.M. Chan, Martyn Pinfold, C.K. Kwong and W.H. Szeto, (2011), "Automation and optimisation of family mould cavity and runner layout design using genetic algorithm and shape grammar", *Computer-Aided Design* (planned to be submitted after the patent is granted)

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LIST OF ABBREVIATIONS

Short Form	**Long Form**
2D	2-Dimensional
3D	3-Dimensional
ABS	Acrylonitrile Butadiene Styrene
AI	Artificial Intelligence
AR	Analogical Reasoning
BB	Branch and Bound search technique
BOM	Bill of Material
CAD	Computer-Aided Drafting or Design
CAE	Computer-Aided Engineering
CAS	Computer-Aided Sculpting
CBR	Case-Based Reasoning
CFP	Cavity Flow Path
CNC	Computer Numerical Control
CP	Cost Performance
CMLD	Conceptual Mould Layout Design
ED	Evolutionary Design
FPBR	Flow Path Balance Ratio
FMCRLD	Family Mould Cavity and Runner Layout Design
FP	Flow Path
GA	Genetic Algorithm
GADYM	Gender-Age structure, Dynamic parameter tuning and Mandatory
GBA	Gradient-Based Algorithm
GGA	Grouping Genetic Algorithm
HR	Heuristic Rule-based algorithm
HVAC	Heat, Ventilation and Air Conditioning
ICMLDS	Intelligent Conceptual Mould Layout Design System
IR	Iterative Redesign methodology
KBE	Knowledge-Based Engineering
LP	Linear Programming method
MCAD	Mechanical Computer-Aided Drafting or Design
MHS	Meta-Heuristic Search techniques
NLP	Non-Linear Programming

OR	Operation Research
PDT	Parametric Design Template
PLM	Product Lifecycle Management
PVC	Polyvinyl Chloride
RBR	Rule-Based Reasoning
RDBR	Runner Diameter Balance Ratio
RFP	Runner Flow Path
RW	Replace the Worst
SA	Simulated Annealing
SEDM	Systematic Engineering Design Method
SG	Shape Grammar
SSGA	Steady-State Genetic Algorithm
SPA	Space Allocation
TO	Traditional Optimisation
TS	Tabu Search
VLSI	Very Large Scale Integrated circuit

1 INTRODUCTION

This chapter describes the background and motivation of this research. The background of the supporting company is briefly introduced in Section 1.1. An overview of today's business environment in the mould making industry is given in Section 1.2. The art of Conceptual Mould Layout Design (CMLD) is presented in Section 1.3. The critical market gaps and knowledge gaps in CMLD are identified and discussed in Section 1.4. Finally, the objectives and scope of this research are specified in Section 1.5.

1.1 Company background

Luen Shing Tools Limited* is a mould making company established in Hong Kong. A 500,000 square foot factory plant with a large team of engineers and mould makers is located in Mainland China. Luen Shing produces, on average, over a thousand plastic injection moulds annually† for a wide variety of industries, ranging from toys,

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* *More detailed information about Luen Shing Tools Limited can be found on the company web-site: (www.luenshing.com.hk).*

† *Based on the total sales figures of plastic injection moulds in Luen Shing Tools limited from 2008-2010.*

electronics, telecommunication and medical to automotive. Figure 1 shows a photo of a plastic injection mould made by Luen Shing Tools Limited.

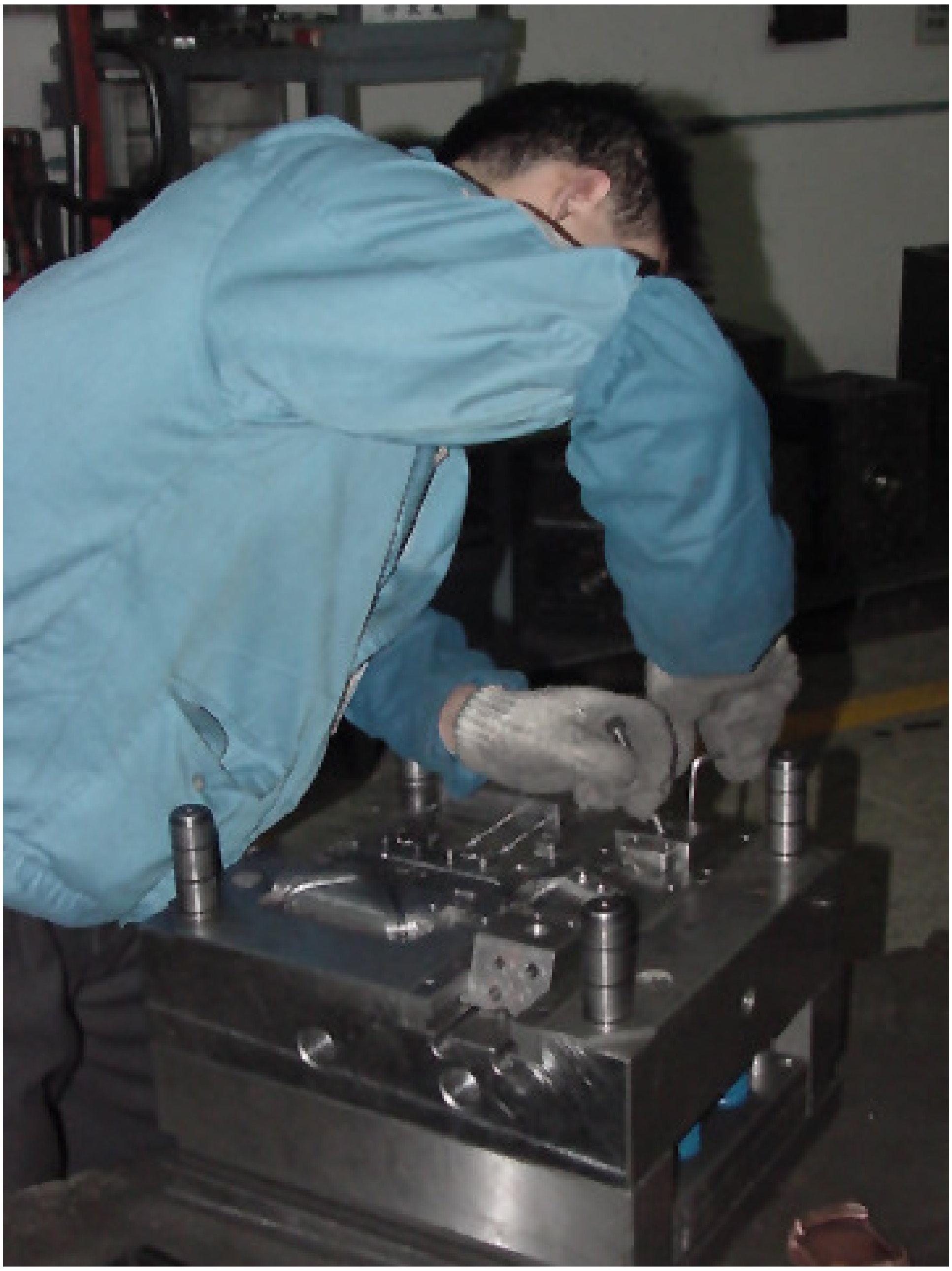

Figure 1. A photo of a plastic injection mould (*Courtesy: the supporting company*)

1.2 Existing business challenges in the mould making industry[*]

Modern mould manufacturing involves high investment in not only advanced software and hardware technologies for mould design and manufacturing, but also a team of experienced engineers and technical staff. During the past ten years, the supporting company has made use of local experienced engineers and technical staff in Hong Kong combined with a low-cost workforce in China to grow its business and maintain its competitive advantage. However, due to the fast-growing manufacturing industry in China, a rapid growth of small and medium local mould shops, which can produce low-end and mid-range injection moulds only, caused not only a price war but also imbalanced human resource demand and supply in the mould making market in China. As a result, the company has been suffering from a fast turnover rate of technical staff and a shortage of experienced engineers over the years. In addition, these local mould shops' capabilities and efficiency of design and manufacturing of injection moulds have been improving since the China government

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[*] *A more detailed discussion of business challenges in the mould making industry can be found in Section 1.2 of the 1st portfolio submission – Research project proposal.*

implemented a strategic plan[*] to support the local mould industry[†] five years ago. Consequently, the supporting company's competitive advantage will decline gradually if this difficult situation continues. After the initial recovery from the severe global financial crisis, the company is facing high inflation pressure in 2011. Unfortunately, the recent crisis in Japan and the turmoil in Middle Eastern countries and Libya have added extra economic uncertainty for the future. The continuously rising cost of raw material, labour and energy is lowering the company's profit margin dramatically. It is more difficult for mould making companies to survive in today's business environment. In today's highly competitive market, rapid response to customers and the achievement of better performance with lower cost have become essential factors for survival. Especially in the toy industry, short time-to-market and low cost are critical. Therefore, the supporting company's major business goals are to retain its existing customers and gain profits by producing error-free family moulds faster, better and cheaper with its existing limited design workforce. However, these business goals cannot be achieved using the company's existing manual mould design methods. The urgent need to innovate the traditional mould design methods for honing the company's competitive edge is the major motivation of this research.

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[*] *In the China government's 11th "Five-Year Plan", one of the major goals is to strengthen local mould shops' capabilities of design and manufacture of mould and die by providing more funding for research and development on this subject in local universities and a special low-interest loan for local mould shops to invest in advanced mould making software and hardware technologies [1].*

[†] *Not including Hong Kong's private-owned mould making companies*

1.3 The art of Conceptual Mould Layout Design (CMLD)

The cost and performance of an injection mould are highly dependent on a Conceptual Mould Layout Design (CMLD)* decision made during the early mould design phase. This is because CMLD determines many key design factors such as cavity layout design, runner layout design, mould base selection, cooling system design and so forth [2, 3]. Mould layout design generally includes all important design decisions affecting the costs, the functions and the manufacturing process plans of a mould throughout a whole mould development life cycle starting from the early quotation phase to final test shot phase. Basically, mould layout design involves many interrelated sub-design tasks: parting-line determination of moulding parts, cavity layout design, runner layout design, tool material selection, mould base selection, cooling system design and ejection system design [3]. As shown in Figure 2, a mould layout drawing is a schematic layout drawing associated with important design information: (a) project and product information, (b) mould layout design sketch, (c) mould design configuration and specification and (d) a table of Bill of Material (BOM). This layout drawing is not only an input of a mould quotation and its detail mould design later, but also a communication and visualisation tool among

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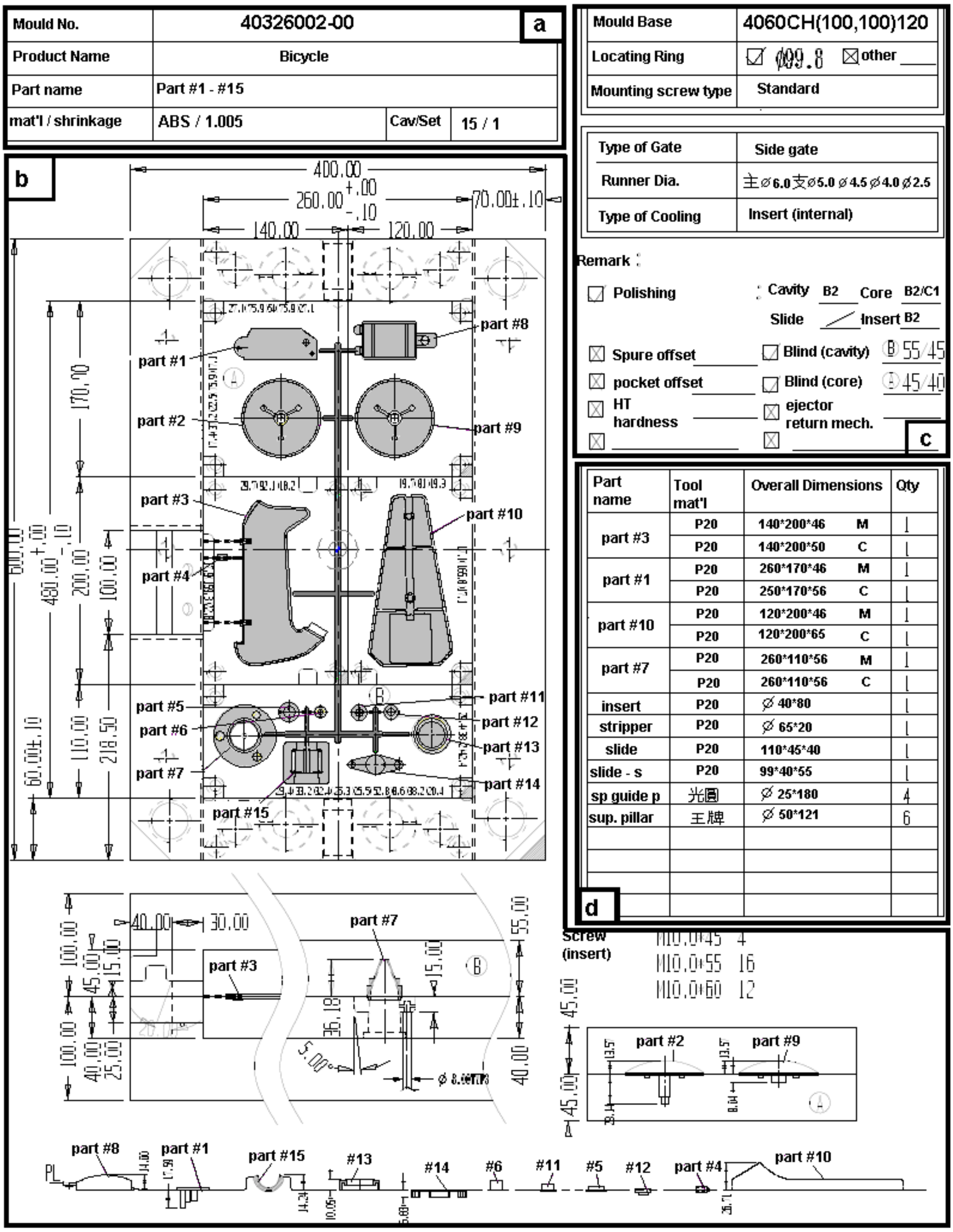
* *A more detailed description of CMLD can be found in Section 1.3 of the 1st portfolio submission – Research project proposal.*

all members of a mould development project.



Mould No.	40326002-00		
Product Name	Bicycle		
Part name	Part #1 - #15		
mat'l / shrinkage	ABS / 1.005	Cav/Set	15 / 1

Mould Base	4060CH(100,100)120
Locating Ring	☑ ∅99.8 ☒ other
Mounting screw type	Standard

Type of Gate	Side gate
Runner Dia.	主∅6.0 支∅5.0 ∅4.5 ∅4.0 ∅2.5
Type of Cooling	Insert (internal)

Remark :

☑ Polishing : Cavity B2 Core B2/C1

Slide / Insert B2

☒ Spure offset

☑ Blind (cavity) B 55/45

☒ pocket offset

☑ Blind (core) A 45/40

☒ HT hardness

☒ ejector return mech.

☒

☒

Part name	Tool mat'l	Overall Dimensions		Qty
part #3	P20	140*200*46	M	1
	P20	140*200*50	C	1
part #1	P20	260*170*46	M	1
	P20	250*170*56	C	1
part #10	P20	120*200*46	M	1
	P20	120*200*65	C	1
part #7	P20	260*110*56	M	1
	P20	260*110*56	C	1
insert	P20	∅ 40*80		1
stripper	P20	∅ 65*20		1
slide	P20	110*45*40		1
slide - s	P20	99*40*55		1
sp guide p	光圓	∅ 25*180		4
sup. pillar	王牌	∅ 50*121		6

Screw (insert)
M10.0*45 4
M10.0*55 16
M10.0*60 12

Figure 2. Real-life example of a mould layout drawing (*Courtesy: the supporting company*)

Figure 3. A photo of a test shot produced by a "One Product Mould" (*Courtesy: the supporting company*)

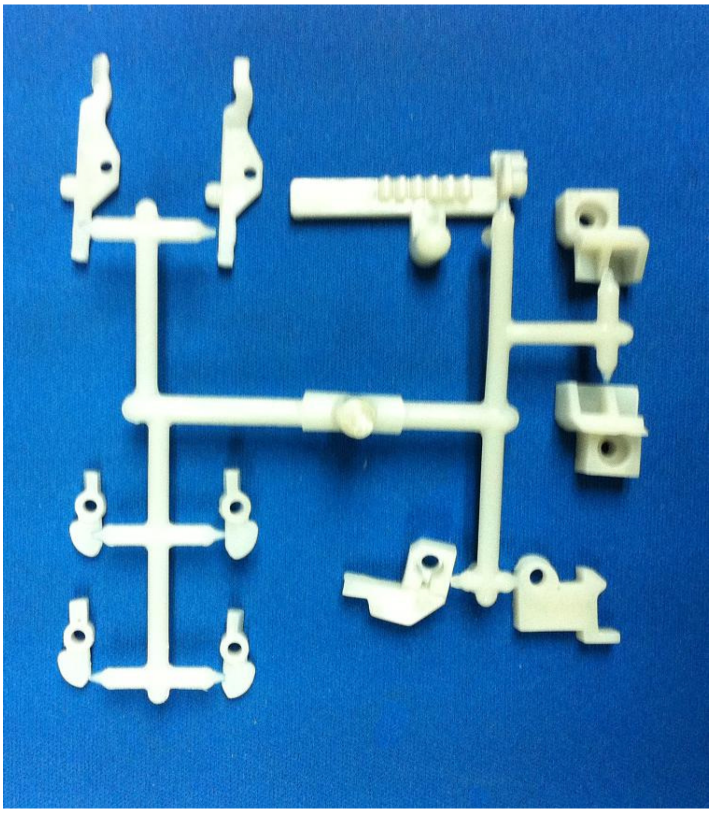


Figure 4. A photo of a test shot produced by a "Family Mould" (*Courtesy: the supporting company*)

As mentioned in Section 1.2, the supporting company produces different types of plastic injection moulds for different products. In general, most of the moulds produced by the company involve multiple cavity layout design.* Figure 3 shows a test shot of a multiple cavity mould, also known as "One Product Mould" which can produce multiple identical parts in one shot. As shown in Figure 4, plastic parts of different shapes and sizes of the same plastic material can be produced in one shot by a "Family Mould". "Family Mould" is widely used in some industries, such as toys and domestic products, because it is an economical method to produce dissimilar parts with a relatively low dimensional accuracy requirement for a small to medium product volume† [4, 5]. From 2008 to 2010, the company produced over 4,000‡ family moulds. "Family Mould" is one of the company's major products.

In CMLD for "Family Mould", cavity layout design is critical because it highly influences many key sub-design tasks such as mould base selection, runner layout design, cooling system design and so forth [6]. Cavity layout is a geometric layout (positions and orientations) of cavities arranged around the sprue associated with a runner layout design. Many standard cavity and runner layout design examples and

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* *A more detailed description of different types of cavity layout designs can be found in Section 1.4.1 of the 1st portfolio submission – Research project proposal.*

† *From experience, the typical production volume of a toys project usually ranges from 100,000 to 1 million shots.*

‡ *Based on the total sales figures of "Family Mould" in the supporting company from 2008-2010*

design guidelines for “One Product Mould”, can be found in the mould design literature [2, 3]. However, no standard layout examples for designing cavity and runner layout of “Family Mould” can be found in the mould design literature [2-5, 7]. This is because Family Mould Cavity and Runner Layout Design (FMCRLD) is unique, non-standard and custom-made. Different family moulds have different design inputs such as the number of cavities, the shapes of moulding parts, the positions and orientations of slides and so forth. Therefore, each family mould must be newly designed to meet its individual design requirements and constraints.

In the supporting company, experienced mould designers have been using various manual design methods to perform FMCRLD for many years. For example, some mould designers like to move and copy the dissimilar cavities represented by simple geometries, such as rectangle and circle, to perform FMCRLD with the aid of ordinary 2-Dimensional (2D) Computer-Aided-Drafting (CAD) software packages or simply by freehand sketching. Some mould designers like to make a set of full-scale paper cards representing the dissimilar cavities and move them around on a table to perform FMCRLD for rapid visualisation of their design. They usually group the dissimilar cavities into several sub-groups according to their size and shape. Then they try out different combinations and locations of each group iteratively until they think that the best visual balance and the smallest overall layout size can be achieved. In fact, mould designers perform this difficult task manually using a trial-and-error method based on their own experience and tacit knowledge. Besides, there is no systematic and efficient training method for FMCRLD. In the supporting company, it usually takes a number of years for new and inexperienced mould designers to become proficient in FMCRLD through learning from experience. Moreover, different designers may produce different FMCRLD. In practice, it is difficult to standardise and evaluate such creative FMCRLD systematically. Therefore, performing FMCRLD can be regarded as a "black art" of family mould design. A good FMCRLD heavily depends on individual talent and intuition resulting in numerous human errors and inconsistencies in layout design in an organization. If a family mould project is not started with an error-free FMCRLD, it will fail. For example, an individual mould designer's mistakes or bad design decisions on FMCRLD at an early design stage may cause some major design defects, such as serious short-shot and out of specification mould base size. If the FMCRLD proves to be totally faulty just before the mould is delivered, it will require extra cost and time to rework the entire mould, involving purchasing a new mould base and tool material, machining the mould cavities and so forth. Besides, the supporting company will also need to pay penalty for every day of delay to its customers. Most importantly, extra man-hours and machine-hours allocated to rework one defective mould will affect production schedules of many other customers' moulds. As a result, the supporting company will waste valuable time, squander limited resources and risk dissatisfying many customers because of one serious design error in FMCRLD. The consequences of serious design errors in FMCRLD can be extremely costly. Therefore, error-free FMCRLD is essential to ensure on-time delivery of error-free family moulds for production.

1.4 Market gaps and knowledge gaps in CMLD*

The aforementioned traditional manual FMCRLD methods and the shortage of experienced mould designers result in long design times, non-optimum designs and many human errors. In addition, rapid loss of company knowledge may happen if there is a high and fast turnover of experienced mould designers. Therefore, a computer-based design tool to assist less experienced mould designers in performing CMLD for family moulds is urgently needed. However, is it available in the current market? Has any related research been done before? Is the realisation of

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* *A more detailed description and discussion of commercial software packages, patented technologies and research on CMLD can be found in Chapter 2 of the 1st portfolio submission – Research project proposal.*

FMCRLD automation and optimisation possible?

Table 1 summarises the findings from the literature review on commercial software packages, patented technologies and previous mould design research with regard to the supportability of CMLD for "Family Mould". The result shows that no commercial solution and patent available in the market can support "Family Mould" (see the shaded rows of Table 1). The rapid and accurate cost estimation of a family mould heavily depends on a quick and good FMCRLD decision made in the early quotation stage. However, no commercial cost estimation tool for family moulds is available in the market because existing cost estimation tools [8-12] and patents [13-16] cannot support FMCRLD and estimate mould cost based on CMLD. Besides, the patented mould design system [17] and existing commercial MCAD software packages [18-35] also cannot support automatic FMCRLD in the CMLD stage. An automated multi-customer moulding system [14] from Protomold® claims that the system can save costs by laying out different parts automatically from different customers on one or more multi-customer family moulds for prototype production of simple parts. However, this patented system cannot address the problems of designing an optimum family mould of more complicated parts for relatively higher volume production. Existing commercial mould flow Computer-Aided Engineering

(CAE) software packages [36, 37] can support optimisation of runner diameters of family moulds based on a given FMCRLD, but they cannot consider the global optimisation of cavity layout, runner lengths and diameters simultaneously. Due to the costly, tedious and time-consuming data preparation for filling balance analysis of numerous different types of FMCRLD, it is virtually impossible for mould designers to use existing commercial CAE software packages to search for the global optimum artificial filling balance solution. To address the limitations of existing artificial filling balance techniques, the patented technologies [38-40] may help moulders to achieve practical filling balance and eliminate shear-induced melt imbalance based on a given FMCRLD during actual production, but most of them are not economic enough to be used in cost-sensitive toys projects. More importantly, it will require extra cost and time to change the FMCRLD afterwards if the failure in filling balance is caused by a bad FMCRLD decision made in the early design stage.

In the field of mould design research, the majority of previous research [41-57, 59-98] focused on individual sub-design tasks as well as integrated mould design for more simple and regular “One Product Mould” while research on cost estimation of “Family Mould” and FMCRLD automation and optimisation has never been reported over the years (see the shaded rows of Table 1). The accurate cost estimation of a family mould heavily depends on rapid and accurate FMCRLD decisions made in the early quotation stage, but no research on this topic has been reported. Tatsuya and Naohiro [58] have attempted to solve the optimisation of cavity layout in three-plate family moulds, but they did not address the more complex problem of FMCRLD for more popular two-plate cold runner family moulds. Over the years, previous research [59–71] has focused on the optimisation of runner size based on a given initial runner layout design regardless of the numerous possible FMCRLD combinations affecting filling balance performance and mould cost. Besides, some researchers [66-71] relied on mould flow CAE simulation results to search for optimum solutions. It is too costly and time-consuming to use mould flow CAE analysis to find the optimum runner and gate design particularly in the early quotation and initial design phases [72]. Many research papers on cooling design [73-85] have been published, but research on cooling design for family moulds has gained little attention. Limited research [86, 87] on ejection design automation and optimisation has been reported over the years. However, ejection design does not influence other sub-design tasks significantly in mould layout design [6]. Previous research on integrated mould design systems [88-93] and design decision support systems [94–98] have demonstrated great potential for guiding engineers to perform mould design. However, none of them can support FMCRLD. Research on automatic initial mould design is very limited, but Ye et al. [98] demonstrated that an automatic initial mould design integrated with a commercial CAD system can act as a guide tool for quotations of moulds as well as their detailed design, and bridge the communication gap between product design engineers and mould designers. However, their research [99] also cannot support FMCRLD.

In conclusion, FMCRLD is critical in CMLD in affecting the mould cost and performance throughout the whole mould development life cycle starting from the early quotation phase to the final test shot phase. However, little effort has been made to study FMCRLD automation and optimisation over the years. FMCRLD automation and optimisation is found to be a critical knowledge gap in the field of mould design research. Further research and development focused on this specific area is urgently needed.

	Commercial software packages							Patented technologies					Previous research							
	MCAD	CAE	Mould costing and quotation					Software system				Hardware system	Mould cost estimation	Parting line design	Cavity layout design	Runner and gate design	Cooling design	Ejection design	Integated mould design	Initial mould design
	[18-35]	[36,37]	[8]	[9]	[10]	[11]	[12]	[13,14]	[15]	[16]	[17]	[38-40]	[41-47]	[48-55]	[56-58]	[59-71]	[73-85]	[86,87]	[88-98]	[99]
Cost estimation based on CMLD	X	---	X	X	X	O	X	O	X	X	---	---	X	---	---	---	---	---	X	X
Parting line design	O	---	---	O	O	O	O	O	---	---	O	---	---	Y	---	---	---	---	Y	Y
Optimum cavity layout design	X	X	X	X	X	X	X	X	---	---	X	---	X	---	X	X	---	---	X	X
Optimum runner and gate design	X	O	---	X	X	X	X	X	X	---	X	---	X	---	X	O	---	---	X	X
Cooling layout design	O	O	---	O	O	O	X	O	---	---	---	---	---	---	---	---	O	---	O	O
Ejection design	O	---	---	O	O	O	X	O	---	---	---	---	---	---	---	---	---	O	O	O
Mould base selection	O	---	O	O	O	O	O	---	---	---	---	---	Y	---	---	---	---	---	Y	Y
Tool material selection	O	---	O	O	O	O	O	---	---	---	---	---	Y	---	---	---	---	---	Y	Y
Artificial fill balancing	---	O	---	---	---	---	---	---	---	---	---	O	---	---	---	O	---	---	---	---

Note: "Y" = Can support family mould, "X" = Cannot support family mould, "O" = Have limitations, "---" = Not applicable

Table 1. Market gaps and knowledge gaps in CMLD

1.5 Research objectives and scope

In order to overcome the business challenges and achieve the business goals, this research aims to automate and optimise the demanding and experience-dependent FMCRLD and thereby improve mould designers' ability and productivity. Thus the supporting company can produce more error-free and optimised family moulds in less time with its existing limited design workforce. However, FMCRLD automation and optimisation is found to be a critical market gap and knowledge gap in the field of CMLD. In an effort to fill these gaps, the primary objectives and scope of this research are:

- To develop an innovative computational approach for supporting FMCRLD automation and optimisation

- To develop a prototype system, named Intelligent Conceptual Mould Layout Design System (ICMLDS), to automate FMCRLD which aims to improve mould designers' ability and productivity in the early quotation phase and CMLD phase

2 RESEARCH METHODOLOGY

This research can be viewed as a process of searching for an innovative solution that can meet the research objectives. Similarly, engineering design process can be regarded as a process of searching for a design solution that can satisfy the design requirements. The Systematic Engineering Design Method (SEDM) [100], which is originally developed for mechanical engineering design, divides engineering design process into four main stages: clarification of the task, conceptual design, embodiment design and detail design. In the SEDM, engineering design process is planned carefully and executed systematically. In order to meet the challenging research objectives in a limited time frame, the process of searching an innovative solution should be planned carefully and executed systematically and logically as engineering design process. Therefore, this research adopts a new mixed research methodology that combines the concepts, tools and techniques of SEDM with traditional qualitative and quantitative research methods [101]. Inspired by the SEDM framework, this research is conducted in four key stages using various research methods and techniques (see Figure 5).

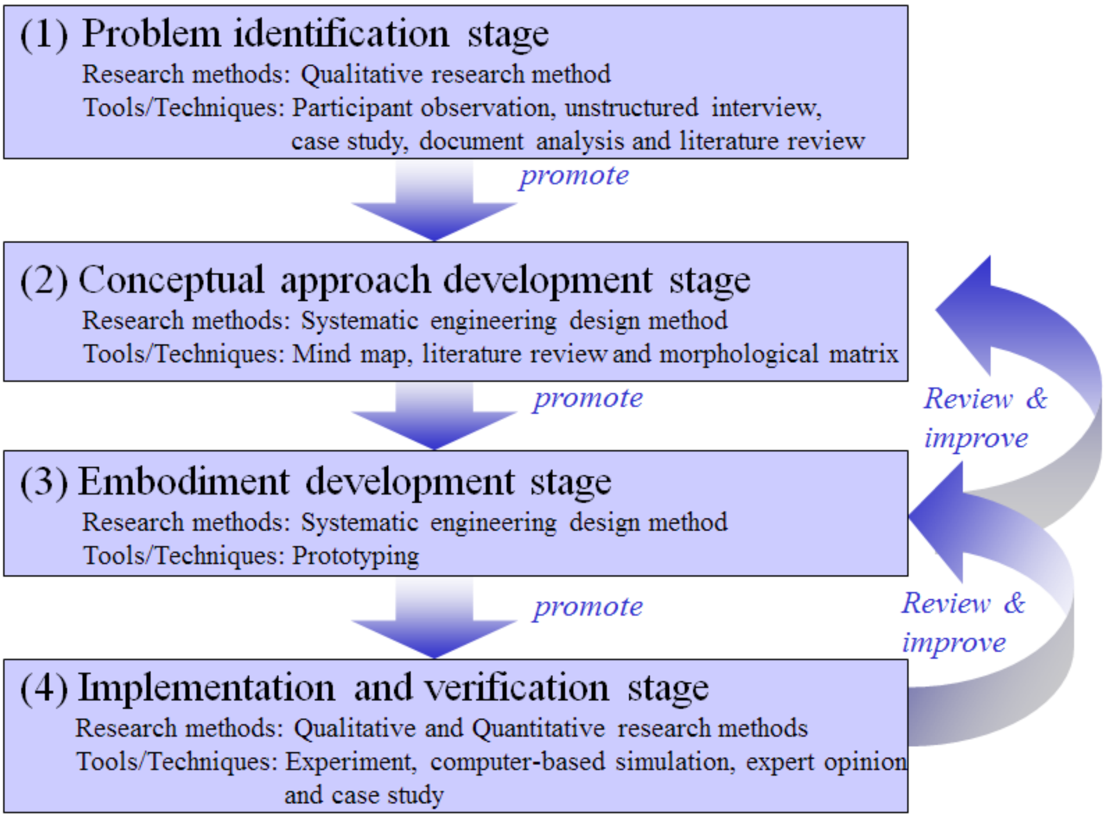

Figure 5. Research methodology flow chart

The first stage aims to identify research problems, find critical market and knowledge gaps, and initiate a research project. As mentioned in Section 1.3, FMCRLD is performed by mould designers using a trial-and-error manual design method based on their own experience and tacit knowledge. Much of design work takes place inside a mould designer's head. In this case, qualitative research method is adopted because qualitative data collection and analysis techniques are good at studying the complexities of human behaviour and issues involving people performing tasks at their workplaces [102, 103]. For example, through participant observations [104], mould designers' behaviour and how they perform day-to-day FMCRLD at their own workplaces can be observed naturally. Unstructured interview [104] can allow mould designers to "speak their mind" and freely express their own ideas and opinions on FMCRLD. This research uses one-to-one unstructured interviews with mould designers in combination with case study [105] and document analysis [106] of past family mould layout design drawings to acquire their tacit knowledge and expert opinions of FMCRLD, and analyse the problems of existing manual FMCRLD methods. The critical market and knowledge gaps in FMCRLD are revealed through a comprehensive literature review on previous research, commercial software packages and patents in relation to family mould design. In the second stage, the conceptual approach development process includes setting research objectives and scope, formulating FMCRLD problems, and generating a conceptual approach. This research uses a mind map[*] technique [107] to graphically visualise, organise and consolidate all the qualitative information obtained in the first stage to formulate FMCRLD problems and identify the functional requirements and characteristics of FMCRLD automation and optimisation. In an attempt to systematically explore possible solutions to the new complex problem, this research uses a morphological matrix technique [100] to review and compare various computational approaches for design automation and optimisation against the functional requirements and

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[*] *A more detailed description of a mind map diagram of FMCRLD problem formulation can be found in Chapter 3 of the author's Post Module Assignment of Innovation Strategy.*

characteristics of FMCRLD. This morphological matrix technique can aid visualisation of a mental picture and generation of an innovative conceptual approach through selection and combination of potential concepts inspired by other field of engineering and science [100]. Subsequently, the conceptual approach is further analysed, refined and developed to form a practical computational approach in the embodiment development stage. During the embodiment development process, the conceptual approach is reviewed and improved iteratively until a feasible computational approach is developed. In the final stage, the prototype system is implemented based on the proposed computational approach. The implementation results are then verified and analysed qualitatively and quantitatively using experiments [103], case studies [105], expert opinions and quantitative mould flow filling simulations [36] with the assistance of a team of mould design experts in the supporting company. Similarly, the prototype system is also reviewed and improved iteratively within the limited time frame of this research until a satisfactory result is obtained.

2.1 Organisation of portfolio submissions

According to the four key development stages as mentioned in the research methodology flow chart (see Figure 5), six portfolio submissions of this research are contextually organised as below:

1. The first portfolio submission *(problem identification stage)*

   Title: Intelligent Conceptual Layout Design System (ICMLDS) - Research project proposal

2. The second portfolio submission *(conceptual approach development stage)*

   Title: A study of FMCLRD automation and optimisation

3. The third portfolio submission *(embodiment development stage)*

   Title: Automation and optimisation of FMCRLD using Shape Grammar (SG) and Genetic Algorithm (GA)

4. The fourth portfolio submission *(implementation and verification stage)*

   Title: Intelligent Conceptual Mould Layout Design System (ICMLDS) implementation and verification

5. The fifth portfolio submission *(summary of the whole research)*

   Title: Intelligent Conceptual Mould Layout Design System (ICMLDS) – Innovation report

6. The sixth portfolio submission *(personal profile of the author)*

   Title: Personal profile

The problem identification stage of this research is reported in the first portfolio submission. The conceptual approach development process is described in the second portfolio submission. The embodiment development process is presented in the third portfolio submission. Detailed descriptions of the implementation and verification of the prototype system can be found in the fourth portfolio submission. The whole research is summarised in the fifth portfolio submission – Innovation report (see Chapters 1-6). In addition, this report explores potential applications of this research (see Chapter 7) and provides prospects for future research not only in the area of mould design but also in other engineering design domains (see Chapter 8). The conclusions are given in Chapter 9. Finally, the author's personal profile is briefly introduced in the sixth portfolio submission.

3 CONCEPT GENERATION AND SELECTION

As concluded in Section 1.4, FMCRLD automation and optimisation is the critical knowledge gap in the field of CMLD. No previous research can support FMCRLD automation and optimisation. This is a new research topic. Therefore, it is important to set the right research direction at the conceptual approach development stage. This chapter summarises how to search for the right research direction to develop an innovative computational approach for FMCRLD automation and optimisation in this research. First of all, the FMCRLD problem formulation is presented in Section 3.1. Then, a comprehensive review of possible computational approaches for FMCLRD automation and optimisation is summarised in Section 3.2. Finally, the conclusion is given in Section 3.3.

3.1 Family Mould Cavity and Runner Layout Design (FMCRLD) problem formulation

As described in Section 1.3, FMCRLD is demanding and experience-dependent. Performing FMCRLD can be regarded as a "black art" of family mould design. In order to formulate the problems of FMCRLD automation and optimisation, this research defined the optimisation objectives and constraints of FMCRLD (see Section 3.1.1) and studied the characteristics and complexities of FMCRLD (see Section 3.1.2). The summary of functional requirements of ICMLDS is given in Section 3.1.3.

3.1.1 Optimisation objectives and constraints

Each family mould is unique, non-standard and custom-made according to different customers' requirements and constraints. In addition, as mentioned in Section 1.4, research on FMCRLD automation and optimisation has gained little attention over the years. Therefore, FMCRLD optimisation objectives and constraints remain unknown. However, some general mould layout design objectives should be considered according to the mould design literature [2, 3]. They are listed as below:

1. To keep the same filling time and melt temperature of all cavities
2. To keep the minimum runner volume for reducing scrap plastic material
3. To keep sufficient space between cavities for cooling lines and ejector pins, and an adequate cross section to withstand the force from injection pressure
4. To keep the sum of all reactive forces in the centre of gravity of the platen
5. To keep the layout as symmetrical as possible for easy designing, manufacturing, cooling and ejection

In addition, other economic design objectives have to be taken into consideration. They are listed as below:

6. To keep the overall size of the cavity layout design as minimal as possible for the limited size of mould base and moulding machines
7. To keep the number of sliders as minimal as possible for the reduction of the cost of making sliders
8. To keep the drop height as minimal as possible for the reduction of cycle time*

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* *In high-speed moulding, drop high differences can become significant for productivity when cycle times are less than 3 seconds [3]*

In practice, FMCRLD also involves two major constraints. They are:

i. Mould base size constraint

ii. Mould layout design constraint

The mould base size constraint must be considered because the maximum allowable mould base size is limited to the space between tie bars on the mould platen of a customer's available moulding machines. This type of restriction can be regarded as a "Geometric Constraint". Besides, FMCRLD also needs to consider the cavity layout and runner layout design restrictions to produce feasible FMCRLD. This kind of restriction is called a "Design Constraint".

3.1.2 Characteristics and complexities of FMCRLD

Traditionally, FMCRLD is a challenging job because it is difficult to place a given number of dissimilar parts in a mould within a minimum space as ingeniously as possible considering all the aforementioned economic and mould layout design goals. For example, a simple family mould of four dissimilar parts already involves a number of possible cavity layout and runner layout design alternatives (see Figure 6). Design alternative (a) seems to be the best one because of its compact and balanced layout, but it requires two individual sliders for Part 2 and Part 3 (see Figure 6a). Design alternative (h) can save cost by combining the two individual sliders into one but at the expense of an unbalanced layout and larger mould base (see Figure 6h). In some cases, a larger mould base is not preferable or even not allowed due to the insufficient space of the mould platen of a customer's moulding machine. On the other hand, it is very important to consider that all dissimilar cavities can be filled at the same time [5, 7]. In practice, a typical runner layout design in a family mould is a hybrid layout of four commonly used runner layout styles: "Fishbone", "H", "X" and "Radial" (see Figure 7). In order to achieve the filling balance, different runner layout designs associated with different cavity layout designs must also be considered at the same time. Therefore, FMCRLD involves considerable combinations of various cavity grouping and layout design alternatives. The number of possible cavity grouping and layout design alternatives increases exponentially with the number of dissimilar parts in a family mould. In addition, different FMCRLD alternatives have different numbers of runner segments and branching nodes. For example, Design alternative (a) contains 6 runner segments and 2 branching nodes while Design alternative (e) has 4 runner segments and no branching node (see Figures 6a and 6e respectively). Therefore, the number of design parameters being optimised will become unknown beforehand and the optimisation search space will become very large if numerous combinations of cavity and runner layout design alternatives have to be taken into consideration. It is virtually impossible for mould designers to try out all possible design alternatives and evaluate all of them one by one manually to find the best trade-off solution between mould performance and cost. In conclusion, optimum FMCRLD can be categorised as a complex multi-level optimisation problem with multiple design objectives and constraints. On the upper level, it is a combinatorial optimisation problem of cavity grouping and layout design, and associated runner layout design (i.e. FMCRLD). On the lower level, it is a parametric optimisation of runner sizes (the number of variables are dependent on the FMCRLD). These characteristics impose great challenges to solve the FMCRLD optimisation problem.

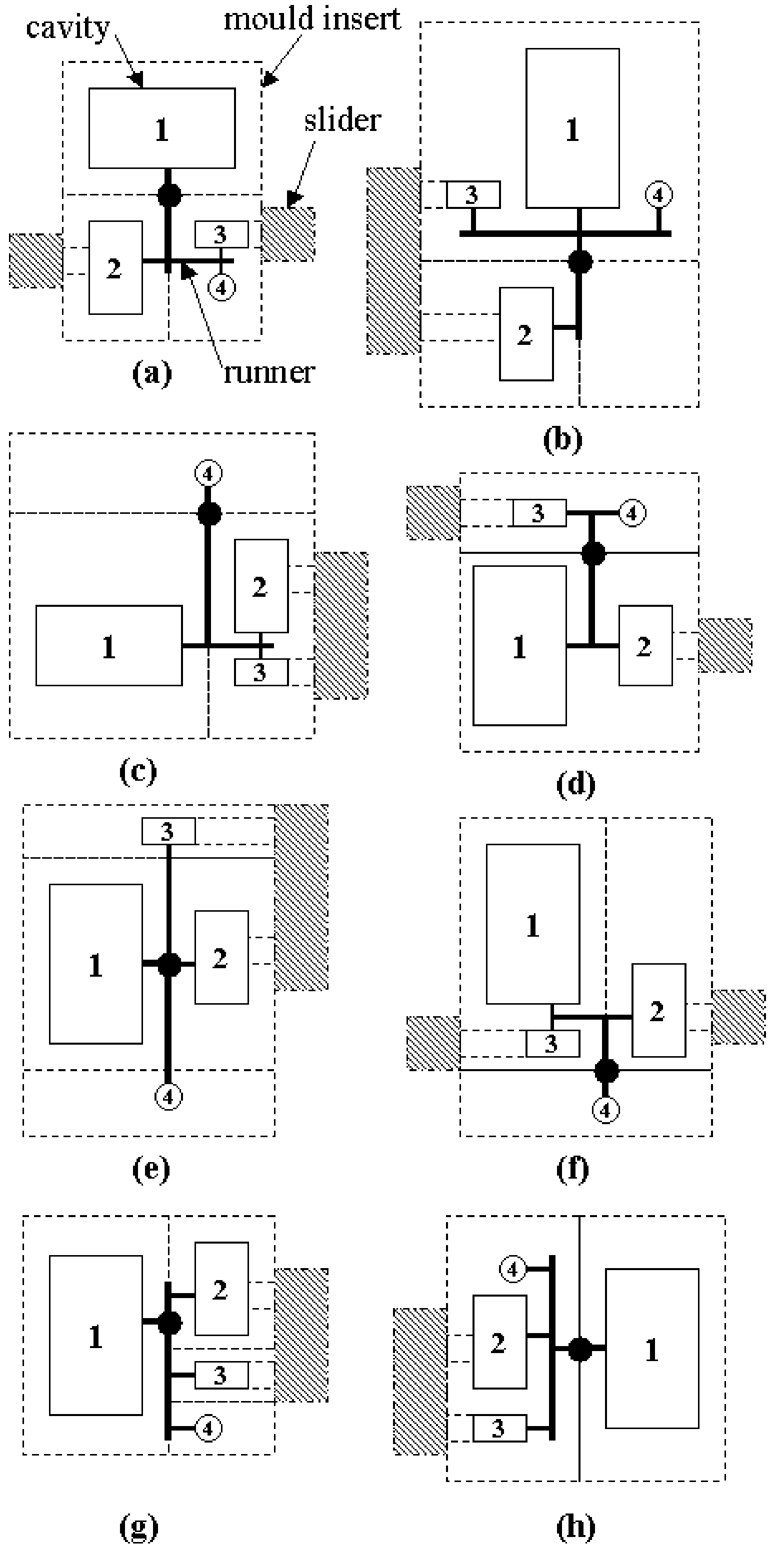

Figure 6. Some examples of possible cavity and runner layout design alternatives of a family mould of four dissimilar parts

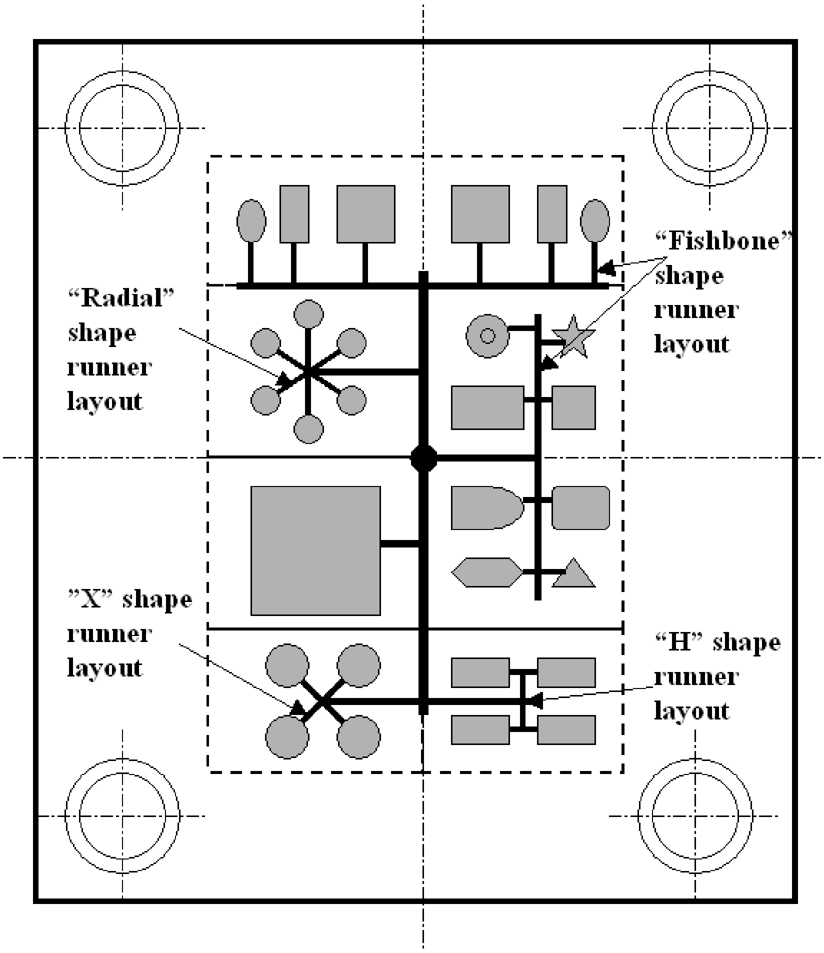

Figure 7. An example of a hybrid layout of four main runner layout styles: "Fishbone", "H", "X" and "Radial" in a family mould

3.1.3 Functional requirements of Intelligent Conceptual Mould Layout Design System (ICMLDS)

As discussed in Section 3.1.2, FMCRLD can be treated as a complex combinatorial layout design optimisation problem with dynamic changing numbers of variables, multiple design objectives and constraints. In contrast to “One Product Mould” design, FMCRLD is non-repetitive and thereby the system must be able to support the automatic generation of unique FMCRLD according to the different design requirements and constraints of each individual family mould. The search space is so large that it is virtually impossible to try out all possible design alternatives and evaluate all of them one by one to find the true global optimum solution. Therefore, the FMCRLD optimisation should aim at searching for a population of “good” designs rather than a single optimal point. In order to achieve the fast response to customers, error-free design and better performance with lower cost, the ICMLDS should provide fast generation of multiple feasible FMCRLD alternatives, rapid visualisation and instant design evaluation for mould designers to accelerate their design alternative exploration and optimisation for better design in less time. Besides, FMCRLD is a complex design process in relation to which mould designers require an explanation of the solution to judge its validity. Moreover, it can be used as an interactive design training tool to train less experienced designers in how to design a good FMCRLD. Due to the shortage of experienced mould designers and the possible rapid loss of FMCRLD knowledge in an organisation, the ICMLDS should have knowledge capture, reuse and learning capabilities. The functional requirements of ICMLDS are summarised as below:

1. Combinatorial layout design optimisation with multiple design objectives and constraints[*]
2. Non-repetitive and generative FMCRLD
3. Fast generation of multiple feasible FMCRLD alternatives
4. Rapid visualization and evaluation for FMCRLD
5. Design explanation
6. Knowledge capture capability
7. Knowledge reuse capability
8. Learning capability

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[*] *The parametric optimisation of runner sizes based on FMCRLD can be obtained by performing artificial filling balance with existing mould flow CAE packages. Therefore, the primary objective is to solve the higher-level optimisation problem of FMCRLD.*

3.2 Search for possible computational approaches for FMCRLD automation and optimisation*

In order to search for possible computational techniques for FMCRLD automation and optimisation, this research has reviewed various computational techniques adopted in previous research in the field of design automation and optimisation not only in the mould design domain but also in other engineering design domains. The comparison of various techniques with respect to the functional requirements and characteristics of FMCRLD automation and optimisation is summarised in a morphological matrix (see Table 2).

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* *A more detailed description and discussion of various design automation and optimisation techniques can be found in Chapter 3 of the 2nd portfolio submission – A study of FMCRLD automation and optimisation.*

	Design automation techniques			Design optimisation techniques								Other special techniques				
	KBE			TO					MHS							ED
Funtional Requirements and characterics of FMCRLD	RBR	CBR	PDT	NLP	IR	LP	BB	GBA	TS	SA	GA	HR	SPA	AR	SG	GA+SG
	[88,89,93]	[56]	[57]	[58,66]	[67,68]	[111]	[112]	[113]	[120-124]	[123-130]	[69-71, 132-140]	[143-148]	[150]	[151]	[153-161]	[162-167]
1 Combinatorial and multi-objective layout design optimisation	---	---	---	O	O	O	O	O	O	O	√	---	---	---	---	√
2 Non-repetitive and generative FMCRLD	X	X	X	---	---	---	---	---	---	---	---	O	O	O	√	√
3 Fast generation of multiple feasible FMCRLD alternatives	X	X	X	---	---	---	---	---	---	---	---	X	X	X	√	√
4 Rapid visualisation and evaluation of FMCRLD	√	√	√	---	---	---	---	---	---	---	---	X	X	O	√	√
5 Design explanation	O	O	O	---	---	---	---	---	---	---	---	√	√	√	√	√
6 Knowledge capture capability	O	O	O	---	---	---	---	---	---	---	---	X	X	X	O	O
7 Knowledge reuse capability	O	O	O	---	---	---	---	---	---	---	---	X	X	X	O	O
8 Learning capability	X	O	X	---	---	---	---	---	---	---	---	X	X	X	X	O

"√" = Support "X" = Not Support "O" = Has Limitations "---" = Not Applicable

non-linear programming, LP linear programming, BB branch and bound, GBA gradient-based algorithms, IR iterative redesign, MHS meta-heuristic search, TS tabu search, SA simulated annealing, GA genetic algorithm, AR analogical reasoning, SPA space allocation, HR heuristic rules, SG shape grammar, ED evolutionary design

Table 2. Comparison of capabilities of various computational approaches for supporting FMCRLD automation and optimisation

3.2.1 Design automation techniques

The Traditional Knowledge-Based Engineering (KBE) approaches, such as Rule-Based Reasoning (RBR) [88, 89 and 93], Case-Based Reasoning (CBR) [56] and simple Parametric Design Template (PDT) [57], have been successfully applied to mould cavity and runner layout design automation of the “One Product Mould”. However, such approaches cannot deal with non-repetitive and generative FMCRLD because the solution space of FMCRLD is large and the design knowledge of FMCRLD cannot be captured, formalised, reused and represented in the form of rules, cases or design templates as efficiently as in “One Product Mould” design. Moreover, the RBR approach cannot support the generation of multiple feasible FMCRLD alternatives by inferring heuristic rules due to the lack of well-formed design methods for FMCRLD. With regard to the CBR approach, no similar design cases can be retrieved efficiently from a large search space because FMCRLD is non-repetitive and generative. Similarly, PDT cannot work in this case because a standard design template cannot be predefined. In other words, the aforementioned traditional design automation approaches cannot produce truly creative, unpredictable or novel design solutions because they are unable to imitate human creativity based on pre-processed human problem-solving knowledge or human-generated solutions.

However, the RBR approach, CBR approach and PDT approach may be applied to the automation of routine geometric modelling and cost estimation of FMCRLD for rapid visualisation and evaluation. Moreover, they can support design explanation limited to some routine sub-design tasks, such as mould base selection, slider design, gate design and so forth. Traditionally, RBR and PDT cannot provide easy mechanisms for automatic machine learning directly, but CBR can achieve it by storing the old cases and adapting to the new cases. Nevertheless, the learning capability of CBR is limited to the representation of the information to be learned. In the case of FMCRLD, the machine learning system may be overloaded due to the large solution space.

3.2.2 Design optimisation techniques

Design optimisation is a large research topic in engineering. An introduction of various engineering optimisation techniques can be found in the literature [108-110]. The section focuses on reviewing some commonly used optimisation techniques adopted in previous research related to FMCRLD optimisation and space layout design optimisation in other application areas, such as strip packing layout design, container stuffing, architectural floor plan layout design, circuit board layout design and so forth.

In the field of mould design, Traditional Optimisation (TO) techniques, such as Non-Linear Programming (NLP) [58, 66] and Iterative Redesign (IR) methodology [67, 68], have been employed to perform the optimisation of a fixed number of design variables (such as coordinates and orientations of cavities [58] and runner sizes [66-68]) based on an initial cavity and runner layout design provided by mould designers. In the field of operation research, other TO techniques, such as Linear Programming (LP) [111], Branch and Bound (BB) [112] and Gradient-Based Algorithms (GBA) [113], have been adopted to find the optimum strip packing layout design and container stuffing. A comprehensive review of various computational approaches to packing layout problems can be found in the literature [114-116]. These TO techniques are efficient in searching for the nearest local optimal solution with respect to the given initial solution. However, they are limited to a narrow class of simple layout problems where explicit mathematical equations describing the objective functions and constraints are available. As mentioned in Section 3.1.2, finding a global optimum FMCRLD cannot be treated as an ordinary design parameter optimisation problem with a fixed number of variables based on a given initial FMCRLD. In addition, some of the FMCRLD objectives and constraints and the interaction among them are difficult to build as true mathematical models required by some of these techniques, such as NLP and LP. More importantly, the search space is combinatorial, large and complex such that FMCRLD optimisation should aim at searching for a population of good designs rather than a single local optimum solution. Therefore, such traditional optimisation techniques are unable to navigate such large search spaces to find near optimum solutions globally and are likely to be inferior local optima.

In order to overcome the limitations of such TO techniques, other researchers focused on seeking optimum layout solutions globally using Meta-Heuristic Search (MHS) techniques, such as Tabu Search (TS), Simulated Annealing (SA) and Genetic Algorithms (GA). TS is a dynamic neighbourhood search technique combined with memory-based strategies [117-119]. It has been successfully applied to many combinatorial component space layout optimisation problems such as the 2D cutting stock problem [120, 121] and 3-Dimensional (3D) bin-packing problem [122]. Meanwhile, SA is an iterative improvement algorithm simulating the metallurgical annealing of heated metals [124]. It has been widely used in circuit layout design [124-126], manufacturing facility layout design [127], 3D mechanical and electro-mechanical component layout design [128] and Heat, Ventilation and Air

Conditioning (HVAC) routing layout design [129]. GA is a stochastic search technique inspired by the biological phenomenon of the natural evolutionary process of survival of the fittest [131]. It has proven to be reliable and able to deal with complex combinatorial and multi-objective layout problems in a wide variety of application areas ranging from runner size optimisation [69-71] and strip packing layout design [132-137] to floor plan layout design [138] and Very-Large-Scale-Integration (VLSI) circuit layout design [139, 140]. More examples of other applications of GA in engineering have been introduced in the literature [108-110].

It is difficult to determine which meta-heuristic method is better suited to tackle the component space layout optimisation problems. This is because the choice of meta-heuristic method is problem-specific and human-dependent. Khumawala et al. [141] and Singh et al. [142] have attempted to compare the relative performance of TS, SA and GA in relation to several classical facility layout problems. The results showed that TS displays very good performance in most cases, but GA can extract more information from fewer solutions than TS and SA. In fact, different meta-heuristic approaches have their own strengths, limitations and features. The main advantage of TS compared with SA and GA is the intelligent use of the past history of the search to influence its future. SA can be almost random in the initial stage and then become more and more deterministic as the temperature decreases. GA is superior to TS and SA because GA can deal with populations of solutions rather than a single solution. Therefore, GA can explore the neighbourhood of the whole population and does not strongly rely on the initial solution. Besides, GA can exchange the information of a large set of parallel solutions in the population through the evolutionary process. Thus GA appears to show great potential to support FMCRLD optimisation.

However, GA is problem-specific and computation-intensive. The performance of GA highly depends on the chromosome design, the genetic operator design, the choice of GA parameters and the weight factors of the evaluation functions [128]. Moreover, the fitness function should correlate closely with the objective function that quantifies the optimality of a solution. Additionally, this fitness function must be computed quickly because GA requires a large number of fitness evaluations to converge to optimum solutions iteratively from generation to generation until the termination conditions are met [116]. According to the multiple optimisation objectives and constraints as defined in Section 3.1.1, filling balance performance is one of the important goals in FMCRLD. However, it is difficult to quantify the filling balance performance of FMCRLD for fitness evaluation in GA. It will become a major issue when using GA for FMCRLD optimisation.

3.2.3 Other special techniques

In addition to TO and MHS techniques, Heuristic Rule-based (HR) algorithms are commonly used to solve specific types of packing and cutting stock problems. Numerous research papers [143-148] demonstrated that they could generate acceptable solutions efficiently based on special heuristic rules derived from common sense or experience. Reviews of the various approaches to tackle the packing problems can be found in the survey papers [114, 115]. However, these HR approaches are only applicable to a specific class of component space layout design problems where well-formed heuristic rules are available. Heuristic rules applicable to FMCRLD remain unknown. Moreover, it is impossible to try all variations of rules to search for optimum solutions that satisfy multiple objectives and constraints. FMCRLD involves not only the ordinary component space layout optimisation problems but also the problems of how to automatically generate multiple good and feasible design solutions that satisfy a number of specific mould design constraints and customers' requirements.

This research discovered that both FMCRLD and architectural space layout design have some common design characteristics and challenges.[*] Similar to FMCRLD, architectural space layout design is the process of allocating a set of space elements and designing topological and geometrical relationships between them according to certain design criteria [149]. Both architectural floor plan layout design and FMCRLD are complex, combinatorial, non-repetitive and human-dependent. Therefore, the research explores potential computational techniques in the field of architectural design.

Over the years, some special computational techniques for improving architectural floor plan layout design have been proposed. For example, Space Allocation (SPA) is a procedural method used to place the space in such a way that the distances between spaces are minimised based on a set of given spaces and the desired adjacency between them [150]. However, this method can only work in very limited areas of architectural floor plan layout design (such as the layout design of hospitals, schools and warehouses) in which quantifiable design objectives can be formulated

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[*] *A more detailed description of the common design characteristics and challenges of FMCRLD and architectural floor plan layout design can be found in Section 3.3.2 of the 2nd portfolio submission – A study of FMCRLD automation and optimisation.*

and where the nature of the solutions is relatively well understood [149]. In FMCRLD, such a complete understanding is difficult to obtain and the design objectives cannot be formulated and quantified explicitly. Arvin and House [151] have proposed the Analogical Reasoning (AR) approach that uses physically based mechanical metaphors to model the elements of architectural floor plan layout design. Their research demonstrated that this special approach could assist designers in analysing and interacting with a layout design by manipulating a graphic model in an interactive and dynamic visualisation environment. However, the set of topological objectives and constraints is limited to how well the mechanical metaphors analogise [149]. Moreover, this approach cannot generate optimum solutions by itself automatically. It just looks for local optima and largely depends on the designer to guide the system into a more optimal configuration interactively [149]. Shape Grammar (SG) [153] is a set of shape replacement rules that can be applied consecutively to generate infinitely many instances of shape arrangements conforming to the specified rules in a non-deterministic manner. Previous research [154-161] demonstrated that SG is an excellent design synthesis tool for design exploration in the field of architectural design. SG can facilitate rapid generation and visualisation of a wide variety of feasible designs using a set of finite shape rules incorporated with human domain knowledge for design exploration, evaluation and explanation.

Therefore, SG has great potential for being a design language used for the exploration of non-repetitive and generative FMCRLD. However, the efficiency of SG heavily relies on well-crafted grammars to decompose the design information to create non-repetitive and complex FMCRLD for different design requirements and constraints. Besides, SG cannot generate designs and learn from old designs automatically by itself. It still requires the user to manipulate different shape rules from a rule set to generate a good design.

In an attempt to generate design automatically, Roseman [162] proposed an Evolutionary Design (ED) approach that uses the GA coupled with a specially designed indirect genotype representation to evolve architectural floor plan layout design. Chouchoulas [163] combined SG with GA to support 3D architectural layout design at the early conceptual design stage. Besides, in other engineering design domains, Bentley and Wakefield [164-166] developed the generic ED system using the GA to evolve a wide range of entirely new and original designs from scratch including example designs of heat sinks, optical prisms, aerodynamic cars and more. More detailed discussions in relation to using the GA for generative design can be found in the literature [167, 168]. Previous works have demonstrated that the ED approach can allow for the generation of meaningful solutions with regard to some requirements formulated in a fitness function [169]. Besides, the specially designed indirect genotype representation incorporated with human domain knowledge can simplify the solution space substantially and thus improve the search efficiency in the GA [168]. This approach enables the GA to synthesise a number of different feasible design alternatives for visualisation, evaluation and explanation. Moreover, the indirect genotype representation may result in large and unexpected changes in the design solutions. This is a desirable property for creative, unpredictable or novel design [168]. Besides, this approach can learn automatically how to manipulate the shape rules to design good FMCRLD by the creation and exploration of novel FMCRLD meeting the specific design objectives and constraints during the evolutionary process. However, both SG and GA are problem-specific and inherit the limitations from SG and GA as discussed previously. The ED approach, which can facilitate an explorative and generative design process embodied in a stochastic evolutionary search, shows great potential to support FMCRLD automation and optimisation. However, the realisation of this innovative approach for FMCRLD automation and optimisation is full of challenges.

3.3 Conclusion

This research characterises that FMCRLD is non-repetitive and generative. FMCRLD optimisation should be treated as a complex combinatorial layout design optimisation problem with a dynamic changing number of variables, multiple mould design objectives and constraints. Considering the business goals and challenges, the functional requirements of the ICMLDS are specified. In order to explore possible computational techniques for FMCRLD automation and optimisation, this research reviews various design automation and optimisation techniques concerning the functional requirements and characteristics of FMCRLD. The review discovers that the Evolutionary Design (ED) approach using GA combined with SG, which was originally proposed for evolving architectural floor plan layout design, reveals a new opportunity to automate and optimise such complex FMCRLD with its explorative and generative design process embodied in a stochastic evolutionary search. However, implementation of this innovative approach for FMCRLD automation and optimisation is full of challenges. Based on this research direction, this innovative approach is further developed and implemented. The following chapters present how to put this approach into practice.

4 EVOLUTIONARY FMCRLD

This chapter presents how to put this innovative evolutionary FMCRLD approach into practice in 4 sections. First of all, the concept of the proposed approach is briefly introduced in Section 4.1. The critical challenges in this research are discussed in Section 4.2. Then the innovative approaches for solving the critical challenges are presented in Section 4.3. Finally, Section 4.4 describes how to implement the evolutionary FMCRLD approach in practice.

4.1 The concept of the nature-inspired evolutionary FMCRLD*

Every living thing in the natural world is a masterpiece of evolved design [168]. Evolutionary design in nature is the original and best evolutionary design system [168]. Figure 8 shows the concept of evolutionary FMCRLD inspired by nature. In nature, a chromosome is an organised structure of Deoxyribo Nucleic Acid (DNA) and protein [170]. A segment of DNA is called a "Gene" [170]. Genes provide

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* *A more detailed description of the concept of the evolutionary FMCRLD approach can be found in Chapter 4 of the 2nd portfolio submission – A study of FMCRLD automation and optimisation.*

information that instructs an organism how to make an individual in many ways [170]. The process of the generation of form in living systems involves the sequence of coded instructions for selecting and locating different kinds of protein in particular locations [170]. Phenotype is an individual organism's actual observed physical properties decoded from its genotype [170]. In nature, the fitness of an individual organism is measured by its ability to survive and produce offspring in its living environment. Evolution is the process of change in the inherited traits of a population of organisms from one generation to the next driven by three main mechanisms – natural selection, genetic drift and gene flow [170]. Natural selection provides competition between organisms for survival and reproduction. Every generation inherits traits from its parents through genes [170]. Consequently, stronger organisms' genes can be passed on to the next generation while weaker organisms die out. Gene flow is the transfer of genes within and between populations during reproduction through genetic recombination (crossover) [170]. Genetic drift is a random change in alleles (mutation) during reproduction [170]. Taking the happy-face spider as an example, spiders with different colour patterns in many forms of smiles are generated through natural evolution because their predators (the Hawaiian Honeycreeper) are good at searching for the most common morph, the yellow morph [171]. The main driving force behind evolutionary design in nature is

"Survival of the Fittest".

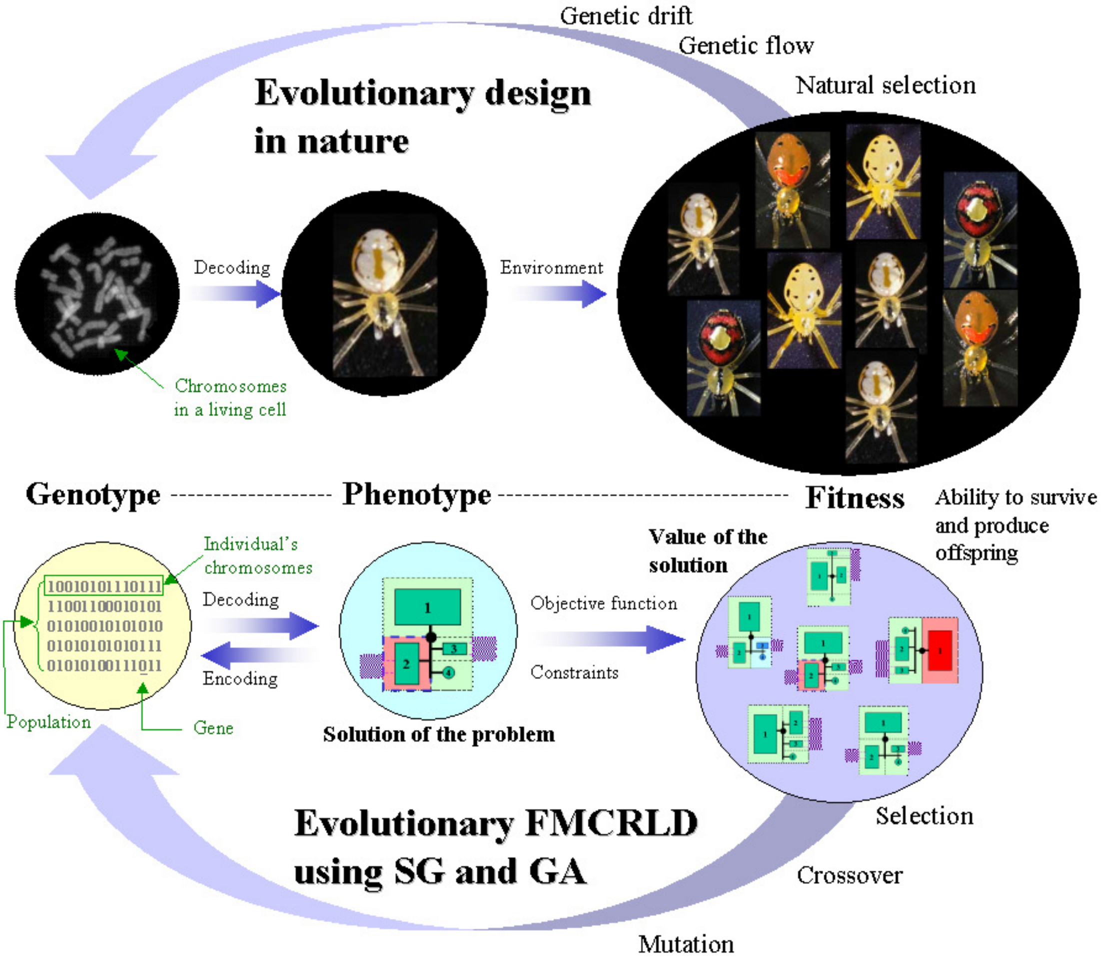

Figure 8. The concept of the nature-inspired evolutionary FMCRLD[*]

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[*] *This upper part of this figure is just for illustration purposes only. The picture of the chromosome shown in the figure is not that of the Hawaii happy-face spider. The photos of the Hawaii happy-face spider shown in this figure are captured from Figure 1 in the literature [171].*

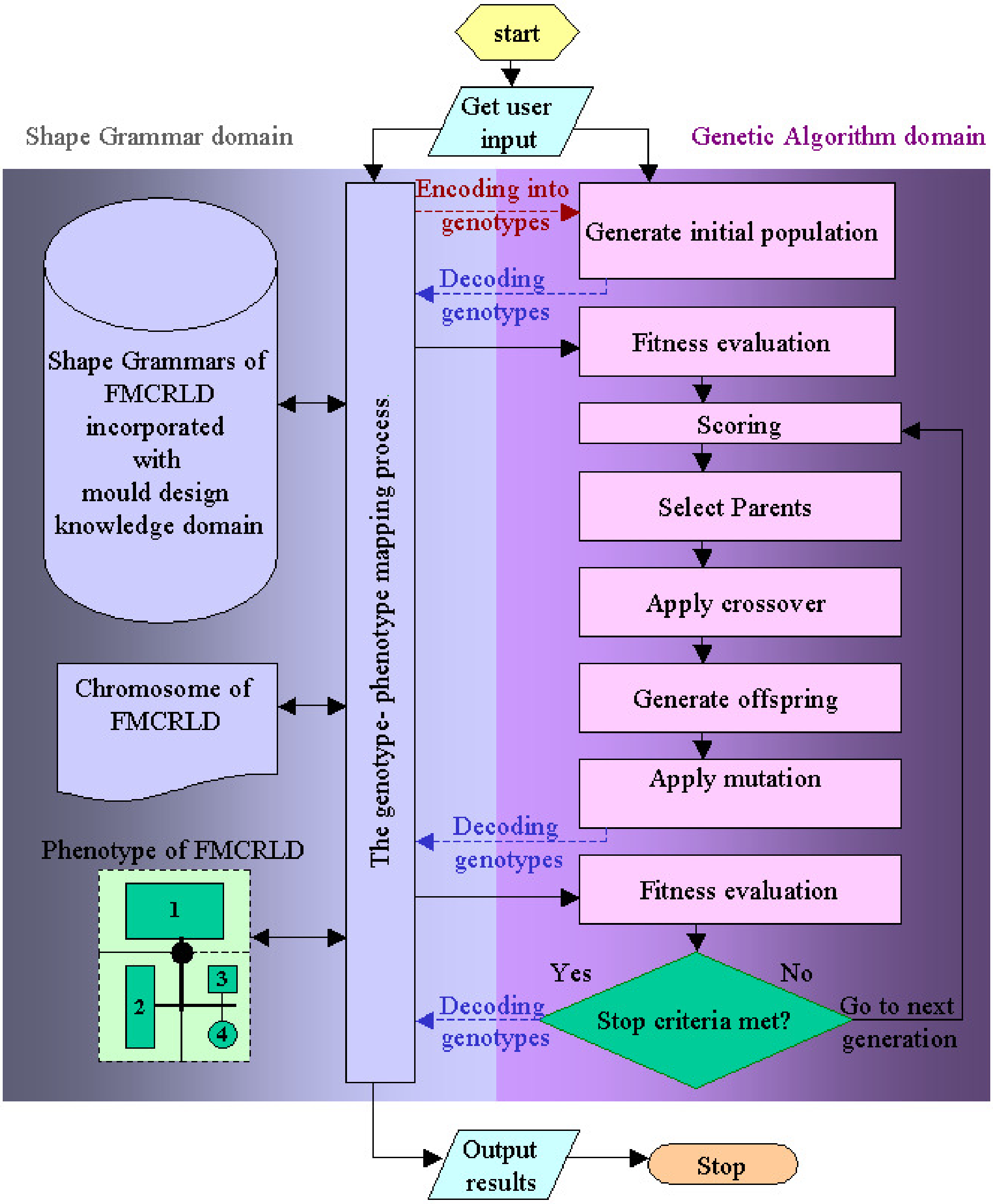

Figure 9. The conceptual program flow chart of the evolutionary FMCRLD

Based on the principle of "Survival of the Fittest", the main concept of the evolutionary FMCRLD is to simulate the natural evolutionary process to evolve FMCRLD using SG and GA (see Figure 9). Analogous to the biological growth of form in living systems as mentioned previously, a gene's locus can be represented by a SG rule while the genotype (recipe) and the FMCRLD solution are represented by the plan (sequence of rules) and phenotype (blueprint) respectively. Each genotype ("control" part) corresponds to a unique phenotype (the body features – the "controlled" part) through the genotype-phenotype mapping process (see Figure 9). The specific SG of FMCRLD incorporated with the mould design knowledge domain provides an encoding/decoding mechanism specially designed for evolving FMCRLD based on a specific chromosome design. The evolutionary process starts by receiving the user input and proceeds to generating an initial population using the SG of FMCRLD. Then the genotypes are transformed into the phenotypes for the fitness evaluation process. A specific scoring scheme is used to quantify the fitness value of each individual in the population considering multiple mould design objectives and constraints. The fittest ("best") members of the population are then selected at random to produce an offspring through the crossover operation. The mutation introduces additional changes into the resulting genotype randomly to generate a new design solution. Weak individuals will be replaced by the better offspring and will disappear eventually during the natural evolutionary process. The selection, crossover and mutation operations are applied repeatedly to the population until the predetermined number of generations is completed or the termination conditions are met. The GA coupled with SG-based chromosomes aims to allow for the generation of feasible and novel FMCRLD solutions and enable the GA to search for optimum solutions more efficiently. This approach can bring together the SG's design synthesis capability and the GA's capabilities of design space navigation and optimisation.

4.2 Challenges in this research*

The concept of the evolutionary FMCRLD approach shows great potential to automate and optimise such complex FMCRLD. However, putting this innovative approach into practice faces three key challenges: (i) Chromosome design, (ii) Genetic operator design and (iii) Fitness function design. Firstly, the efficiency of the GA highly depends on a proper chromosome design for a specific problem [172]. In addition, the usefulness of SG heavily relies on a well-crafted grammar for design representation and synthesis. In other words, a SG-based chromosome design is very problem-specific. Research on the automation and optimisation of FMCRLD using SG and GA has never been reported before. Designing an SG-based

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* *A more detailed description and discussion of the challenges in this research can be found in Chapter 5 of the 2nd portfolio submission – A study of FMCRLD automation and optimisation.*

chromosome for evolutionary FMCRLD from scratch is the first major challenge in this research. Secondly, the efficiency of the GA also depends upon genetic operators that fit the properties of the chromosome well [172]. In this research, simple standard genetic operators cannot be used because of the use of the new and special chromosome design. Designing efficient genetic operators for producing valid offspring that can inherit meaningful “building blocks” from both parents with a new and special SG-based chromosome is very challenging. Thirdly, how to quantify the performance of a large number of FMCRLD alternatives in the population for fitness evaluation in GA will be one of the major challenges in this research.

4.3 Innovative approaches for solving the challenges

In an effort to realise the proposed evolutionary FMCRLD, this research developed innovative approaches for solving the challenges. A novel SG of FMCRLD was developed (see Section 4.3.1). Subsequently, a new chromosome and genetic operators were specially designed for evolutionary FMCRLD (see Sections 4.3.2 and 4.3.3). With regard to the challenge in fitness evaluation of FMCRLD, new approaches for quantifying the cost and performance of FMCRLD are presented in Section 4.3.4.

4.3.1 New generative FMCRLD using Shape Grammar (SG)*

As mentioned in Section 3.1.2, FMCRLD is non-repetitive and generative. Research on SG of FMCRLD has never been reported before. This research pioneered the study of FMCRLD and the use of SG to represent FMCRLD. In current practice, experienced mould designers first group dissimilar cavities into several sub-groups. Then, they determine the locations of each group and design the associated runner

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* *A more detailed description of the SG of FMCRLD can be found in Section 2.1 of the 3rd portfolio submission – Automation and optimisation of FMCRLD using Shape Grammar and Genetic Algorithm*

layout design accordingly. Based on the author's observation and recognition of implicit common layout design features from a number of practical FMCRLD examples, a novel SG of FMCRLD integrated with mould layout design knowledge has been crafted. The main concept of the proposed SG is to synthesise generative FMCRLD by manipulating three sets of interdependent SG – (i) group layout design SG, (ii) internal group layout design SG and (iii) runner layout design SG.

(i) Group layout design SG

A group layout design is decomposed into virtual multi-cavity groups and regions (see Figure 10). The virtual multi-cavity group represents a group of cavities that are filled through the same sub-runner. The virtual multi-cavity group region defines the virtual boundary of different non-overlapping zones allocated around the virtual centre of the mould base (also the sprue location). A virtual multi-cavity group is represented by a rectangular boundary box. Each individual virtual multi-cavity group containing one or more cavities is placed in 12 different virtual multi-cavity group regions (A-L). Each region can contain more than one virtual cavity group. Based on this concept, the 12 shape placement rules for their corresponding 12 different regions have been developed (see Figure 11).

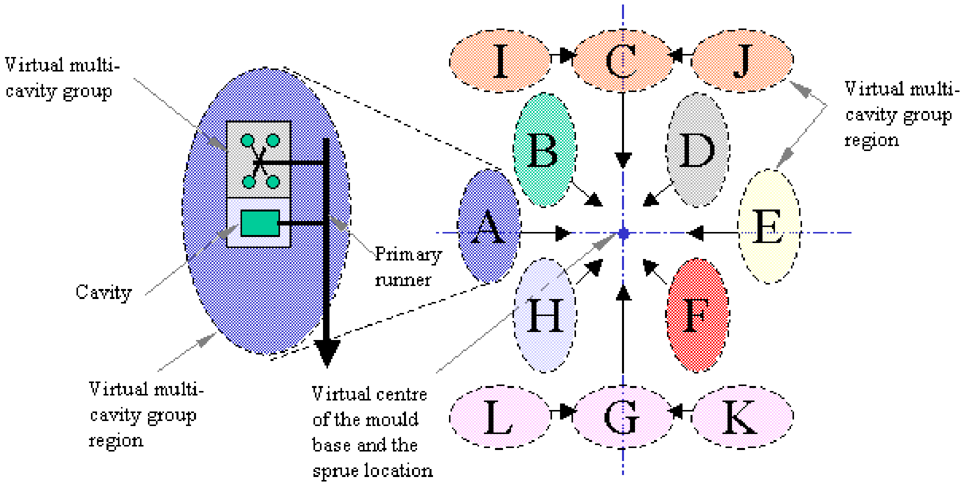


Figure 10. The concept of virtual cavity groups and the 12 main virtual multi-cavity group regions

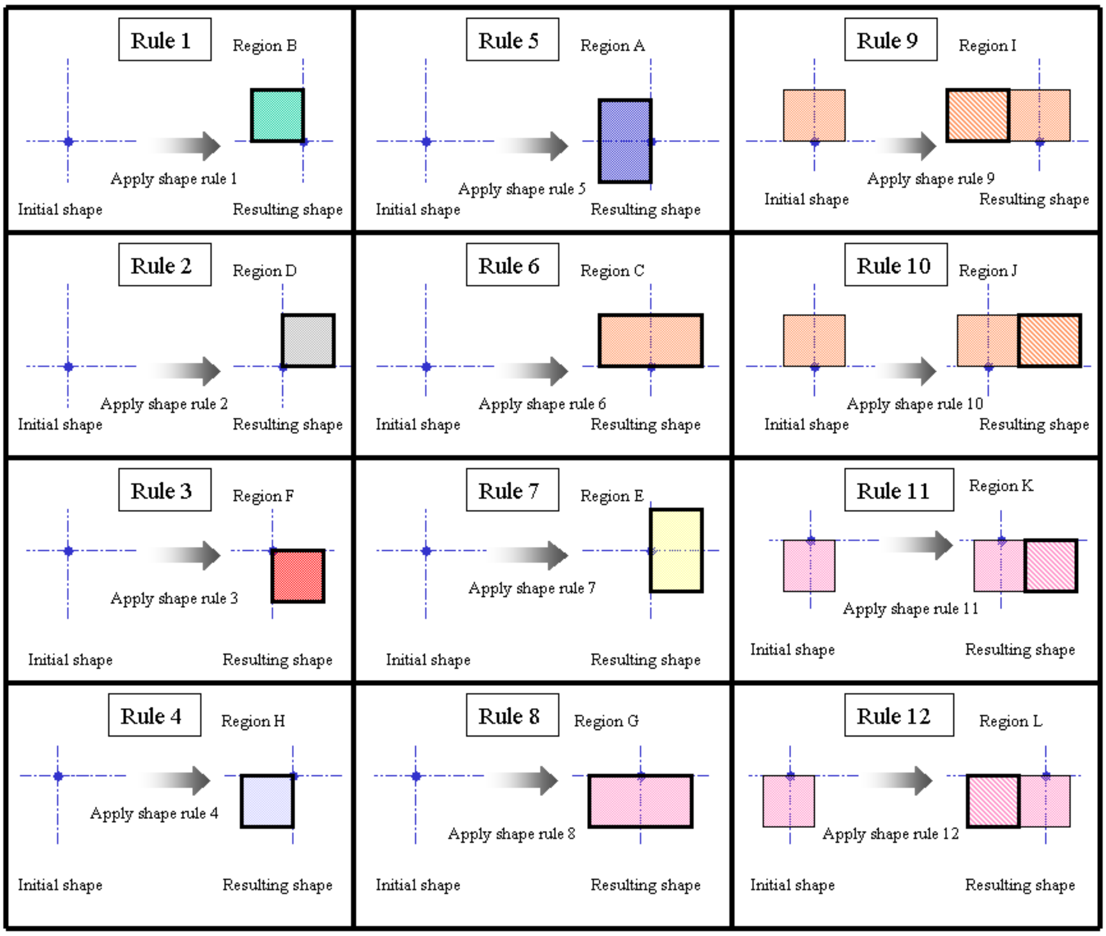


Figure 11. The 12 basic shape placement rules of the proposed group layout shape grammar

The proposed group layout design SG can control the placement of virtual multi-cavity groups in a FMCRLD and generate unlimited numbers of different group layout designs. As illustrated in Figure 12a, if shape placement rule 1 is applied to the initial shape of the centre point of the mould base, the lower right corner of the rectangular box will be aligned to the centre point. Then, if rule 6 is applied to the shape added by rule 1 in the previous step, the rectangular box will be added on top of the box. Subsequently, the resulting group layout design can be generated by applying rules 7, 8 and 4. Another example of the application of various shape placement rules to various initial shapes is illustrated in Figure 12b. Besides, the proposed group layout design SG also can avoid any invalid group layout design. For example, the application of rule 4 is allowed in region H only. Rule 8 can only be applied to the centre point of the mould base in region G if there are no groups placed in regions H or F. Rule 9 can only be applied to the shape added in the previous step in region I. Therefore, a valid group layout can be generated accordingly (see Figure 13b). Figure 13a shows an example of an invalid group layout caused by no restriction on the application of shape placement rules to different initial shapes in different regions.

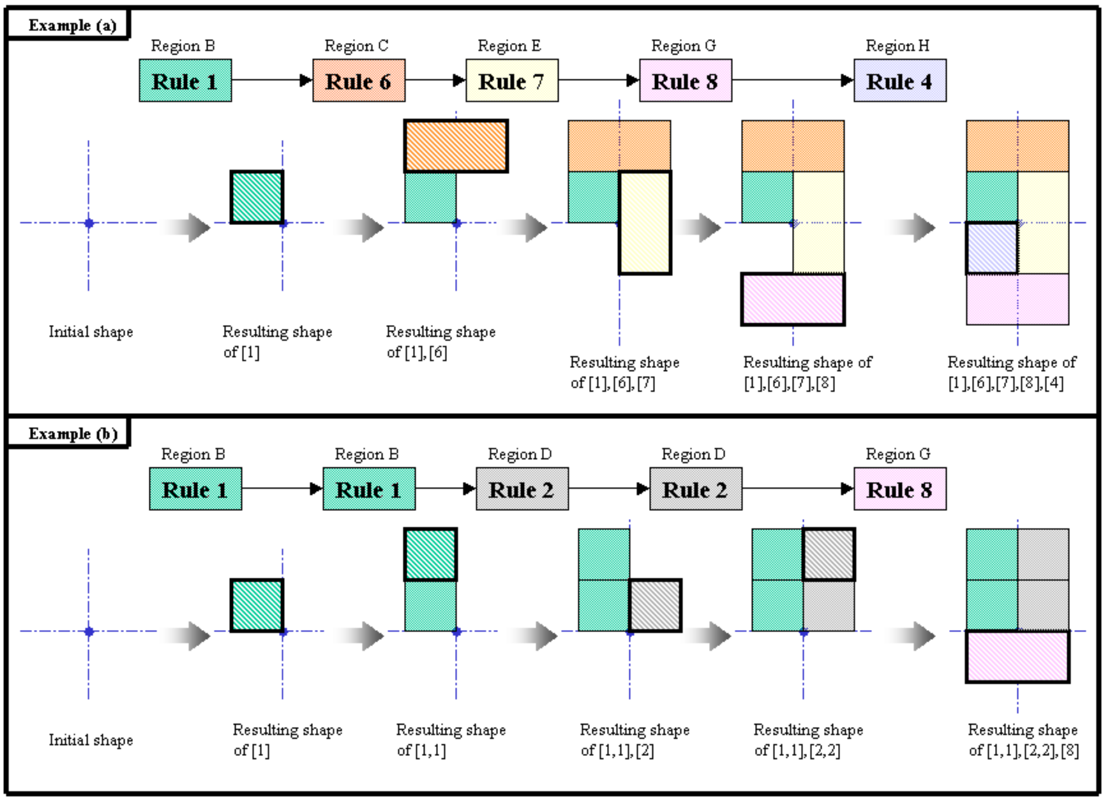


Figure 12. Examples of generation of group layout design using the proposed shape placement rules

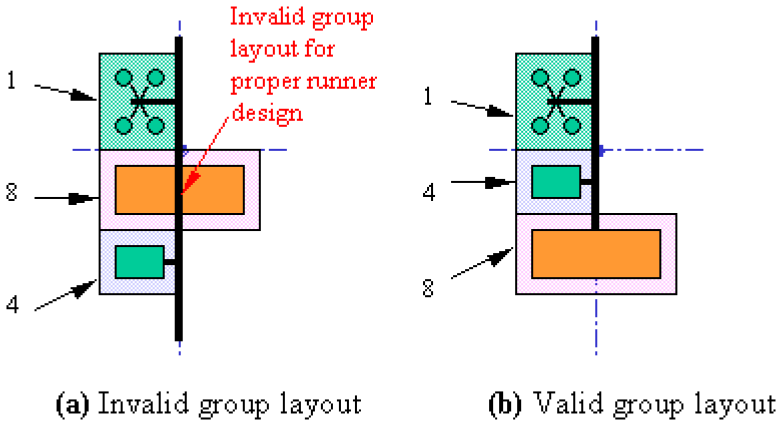
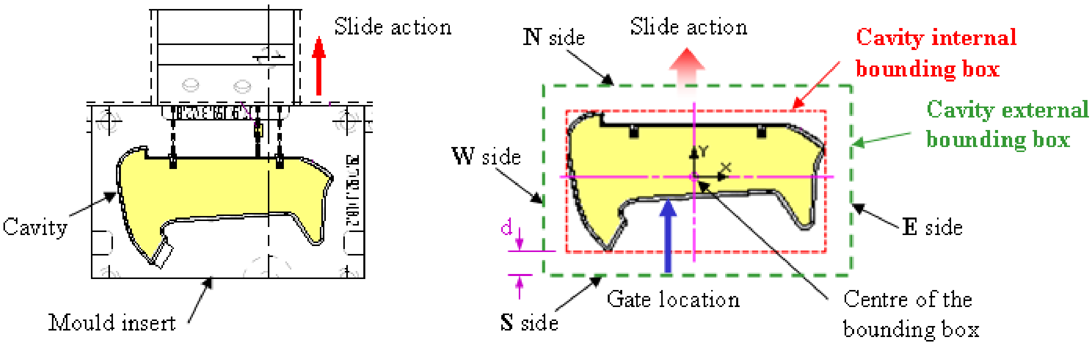


Figure 13. Valid group layout for proper runner design

(ii) Internal group layout SG

In this research, moulding parts are classified into two shape codes: Circular and Rectangular. All circular moulding parts are represented by simple circular cylinders while all irregular moulding parts are represented by rectangular boxes. Figure 14 illustrates how an individual cavity layout design is represented. The cavity internal bounding box equal to the overall size of the moulding part is enclosed by the rectangular virtual cavity external bounding box with an offset distance “d” for sufficient shut-off area and space for runners and cooling channels. The four sides of the external bounding box are denoted by W, N, E and S. Information on the possible gate location and the required slide action is represented by symbols attached to these four sides as shown in Figure 14b.



(a) Real-life example of an individual cavity layout design

(b) Representation of an individual cavity layout design

Figure 14. Representation of an individual cavity layout design

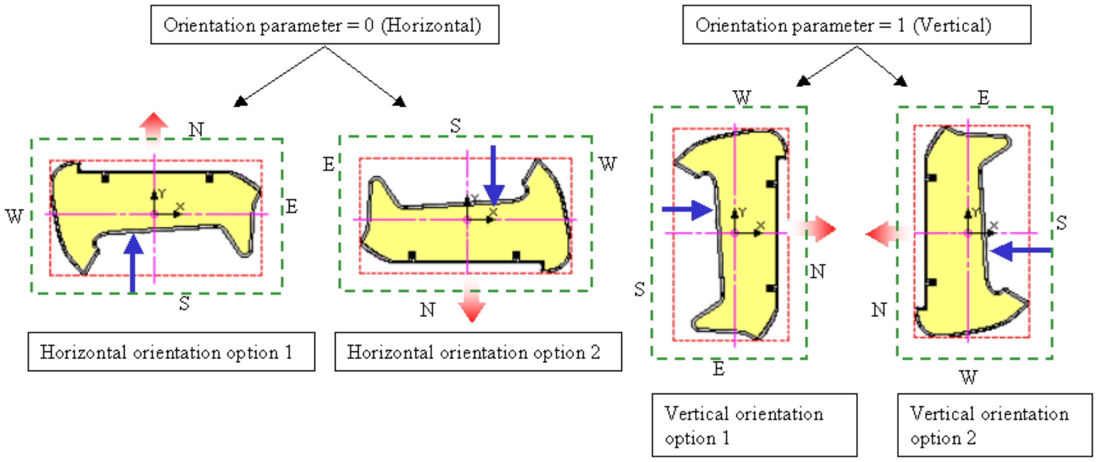


Figure 15. Orientation parameters of an individual cavity

The internal group layout SG aims to control the orientations and location arrangements of multiple cavities in a virtual multi-cavity group. Figure 15 shows four possible orientation options for two orientation parameters: 0 (horizontal) and 1 (vertical). Based on the analysis of common internal group layout features of existing practical FMCRLD, a set of internal group layout SG rules were developed in this research (see Figure 16). The internal group layout SG integrated with cavity layout design knowledge* enables an automatic arrangement of multiple cavities in a virtual multi-cavity group considering the shape code, volumetric size, gate location and slider location of each individual cavity as well as the location of the virtual multi-cavity group.

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* *A more detailed description of internal group layout SG integrated with cavity layout design knowledge can be found in Section 2.4 of the 4th portfolio submission – ICMLDS implementation and verification*

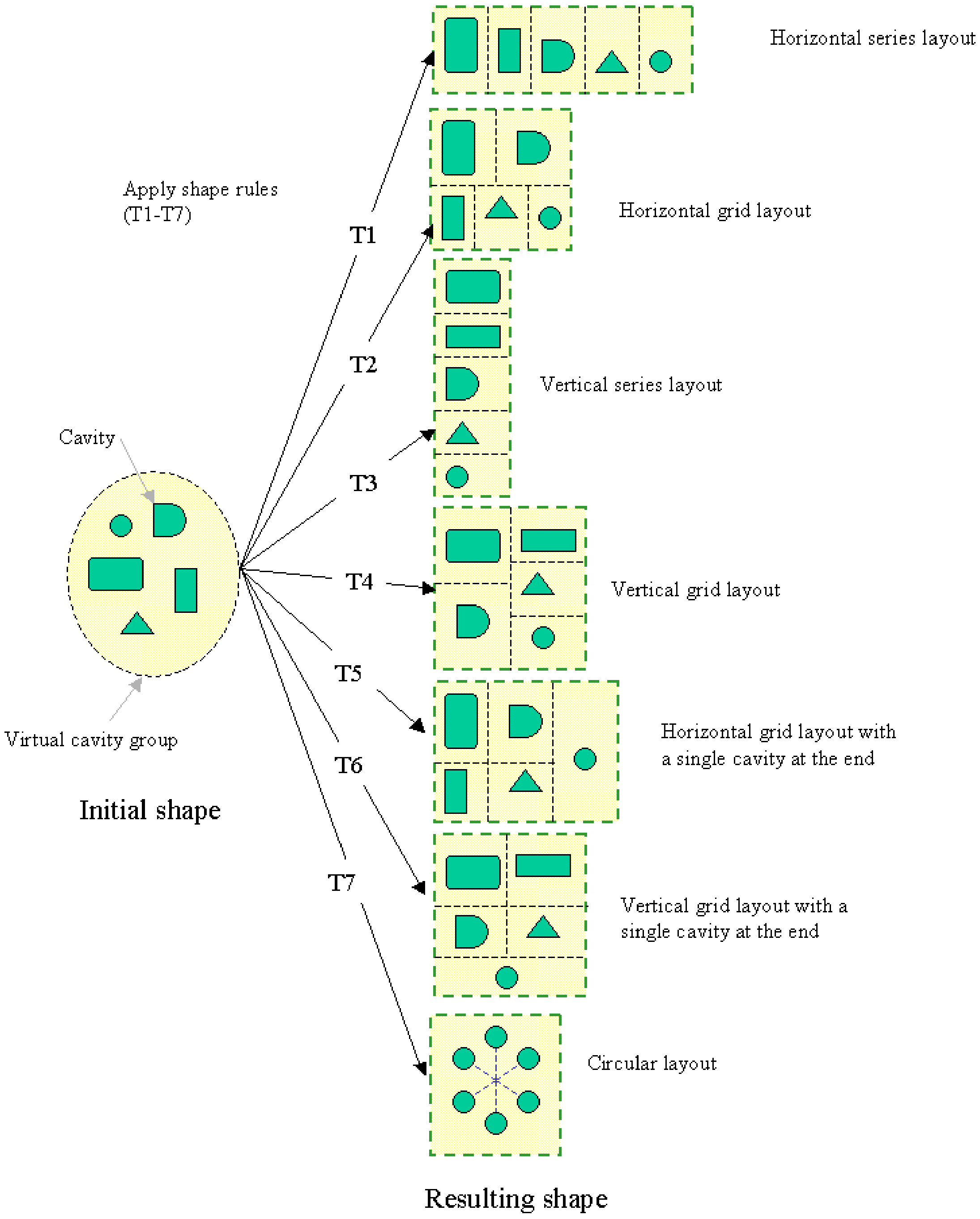

Figure 16. Seven shape rules for internal group cavity layout

(iii) Runner layout SG

As mentioned in Section 3.1.2, family mould runner layout design involves four commonly used runner layout styles: “Fishbone”, “H”, “X” and “Radial” (see Figure 7). Based on these four runner layout styles, a set of runner layout SG rules was developed for automatic generation of feasible runner layout design that can adapt to different cavity layout designs intelligently. For example, the application of runner layout shape rule R1 (“Fishbone” style) to the virtual multi-cavity group with internal cavity group layout rule T2 generates the resulting “Fishbone” style runner layout design (see Example (a) in Figure 17). If the internal cavity group layout rule is changed from T2 to T1, the resulting “Fishbone” style runner design can be changed accordingly (see Example (b) in Figure 17).

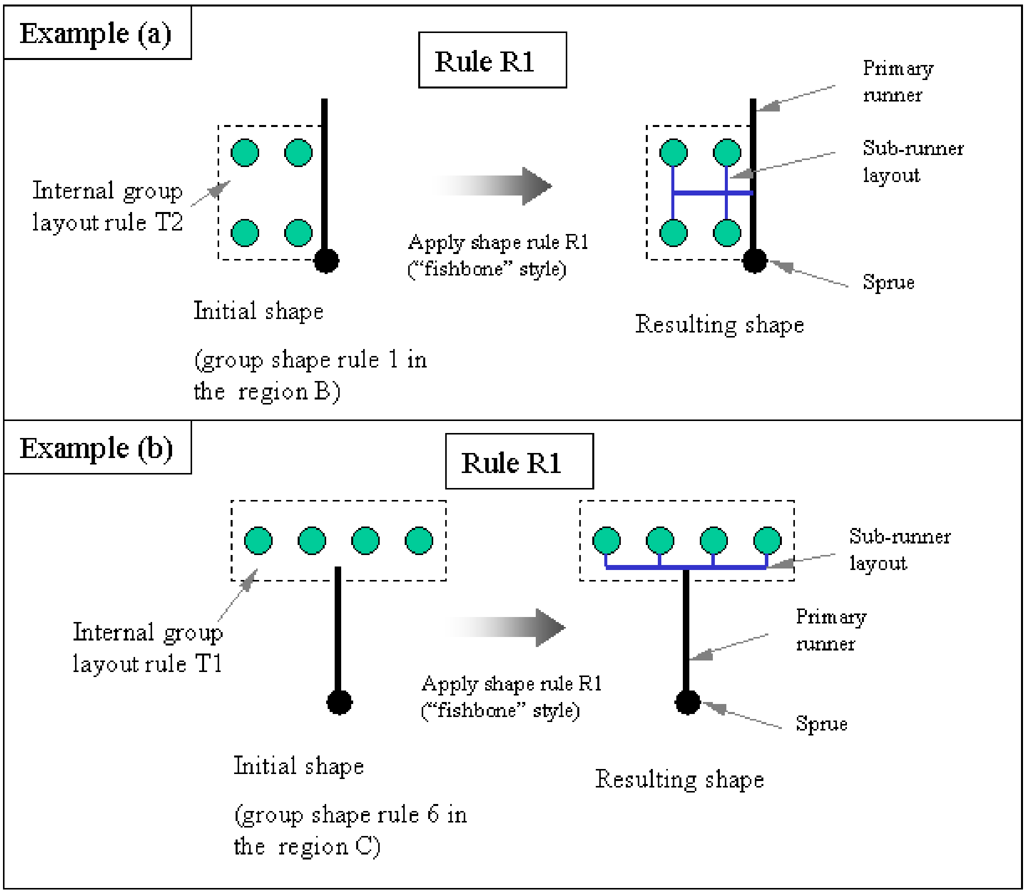

Figure 17. Examples of application of the runner layout SG rules

As summarised in Figure 18, the application of the runner layout SG rules to virtual multi-cavity groups with different numbers of cavities and various internal group layout rules can generate a number of different runner layout designs. Some general rules for application of specific runner layout SG rules are used to avoid invalid runner layout designs. For example, R2 ("H" style) or R3 ("X" style) can only be applied to a cavity group containing four or eight cavities with layout rule T2 or T4. R4 ("Radial" style) is only valid for cavity groups with three or more identical circular parts.

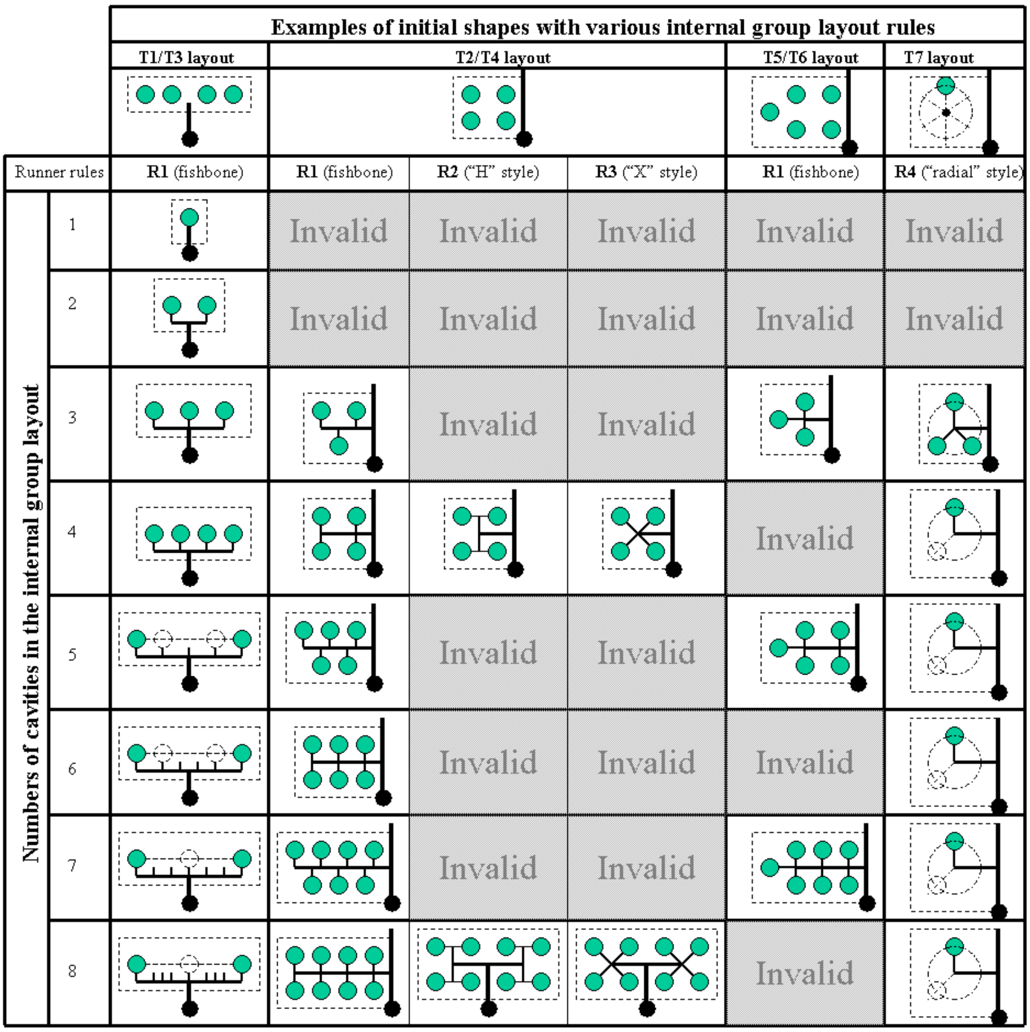

Figure 18. Summary of runner layout SG rules applied to various initial internal group cavity layouts

The aforementioned SG of FMCRLD can be used to synthesise a feasible cavity layout design in a family mould. As illustrated in Figure 19, the layout of six virtual multi-cavity groups is generated by the application of six different shape placement rules (1, 6, 7, 3, 4 and 4) in five different regions (C, B, H, E and F). The six virtual multi-cavity groups are filled through the six individual "Fishbone" style secondary runners branched from the primary runner. Different cavities in each individual virtual multi-cavity group are filled locally through its sub-runner system generated using the runner layout shape rules (R1, R4 and R2) associated with the internal cavity group layout shape rules (T1, T2, T3, T4, T5 and T7). For better filling balancing and clamping force balancing, internal group SG rule T1 can automatically place a cavity with a bigger size closer to the vertical centre position considering the volumetric size of dissimilar cavities and group layout rule 6 in Region C. Similarly, internal group SG rule T1 combined with group layout rule 4 in Region H can place a cavity with a bigger size closer to the horizontal centre position. Internal group SG rule T4 combined with group layout rule 7 in Region E can intelligently not only place a cavity with a bigger size closer to the horizontal centre position but also place two cavities with external sliding action close together and near the outside group boundary for easy and economic fabrication of the slider. If the number of sliders on each side of the mould is more than one, all the sliders will be grouped into one slider. Using different combinations of the proposed SG rule applications and various configurations of the virtual multi-cavity groups including the number of groups and the content of each group can generate a large number of different family mould cavity layout designs.

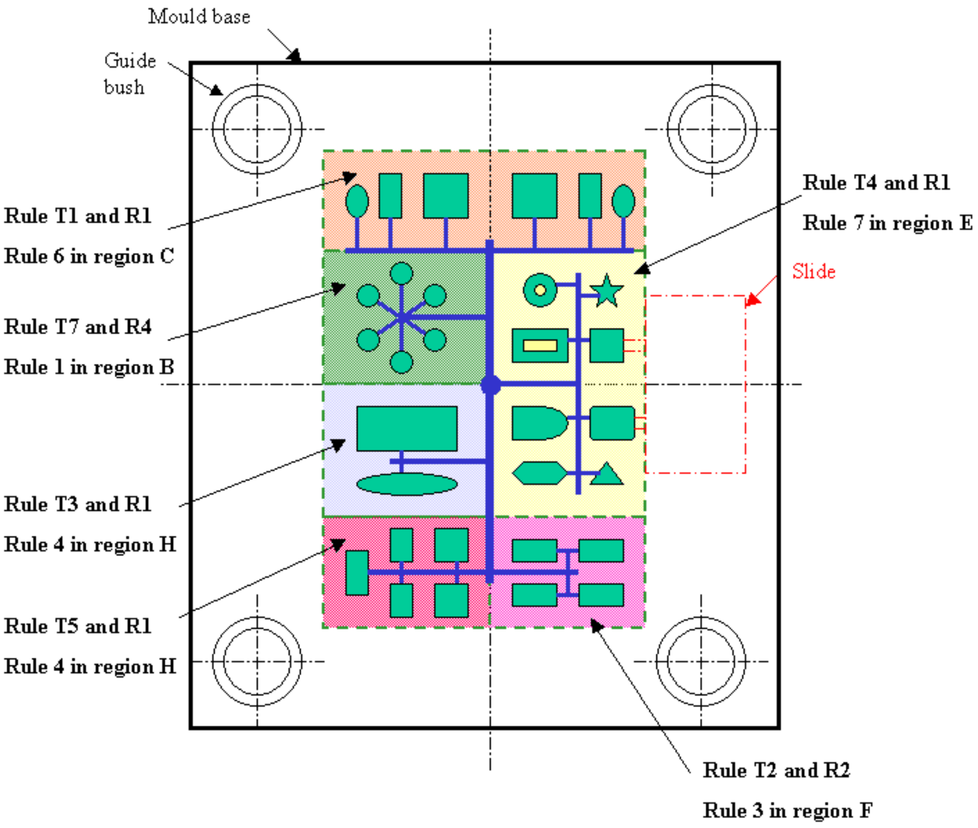

Figure 19. An example of an FMCRLD using the proposed SG of FMCRLD

4.3.2 New chromosome design[*]

The configuration of virtual multi-cavity groups can be considered a combinatorial grouping design problem involving a large number of possible combinations of different numbers of groups and different content of each group. In order to encode not only the geometrical layout design information but also the cavity grouping design information in FMCRLD, this research developed a new hybrid SG-based chromosome that consists of three interdependent chromosome sessions - (a) Orientation session, (b) Group session and (c) Group layout shape rules session. Figure 20 shows the mapping of the graphical phenotype representation with its corresponding chromosome session. The orientation session of the chromosome contains orientation information of each individual cavity in a family mould. The locus (position) of the gene represents the part identification number. The allele of the gene is the part's orientation parameter as defined in Section 4.3.1. The length of this session is fixed because it is equal to the number of moulding parts. The cavity grouping design information is stored in the group session where the locus of the gene represents the part identification number and the allele of the gene is the part's group identification number. In the group layout shape rules session, the locus of the gene

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[*] *A more detailed description of the chromosome design can be found in Section 2.2 of the 3rd portfolio submission – Automation and optimisation of FMCRLD using Shape Grammar and Genetic Algorithm*

represents the group identification number on a one-gene-for-one-group basis. The length of this session is variable because the number of groups is variable. In each gene, the three rule number labels enclosed in parenthesis represent the group layout SG rule, the internal cavity group layout SG rule and the runner layout SG rule (see Section 4.3.1) of their corresponding group, respectively. Using the SG of FMCRLD, the genotype can be decoded to form the phenotype as shown in Figure 19. The main advantage of using this new hybrid chromosome is that the "Orientation session" and the "Group session" can represent the part's orientation and the cavity grouping design while the associated "Group layout shape rules session" can represent the geometrical layout design with minimum redundancy.* Moreover, the solution space can be reduced because this new hybrid SG-based chromosome design enables all individuals generated in the population to be feasible solutions conforming to the SG of FMCRLD.

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* *Redundancy means that one design solution (phenotype) is represented by more than one genotype [172]. In this research, each individual cavity layout design solution should be represented by as few distinct chromosomes (ideally exact one) as possible in order to reduce the size of the search space.*

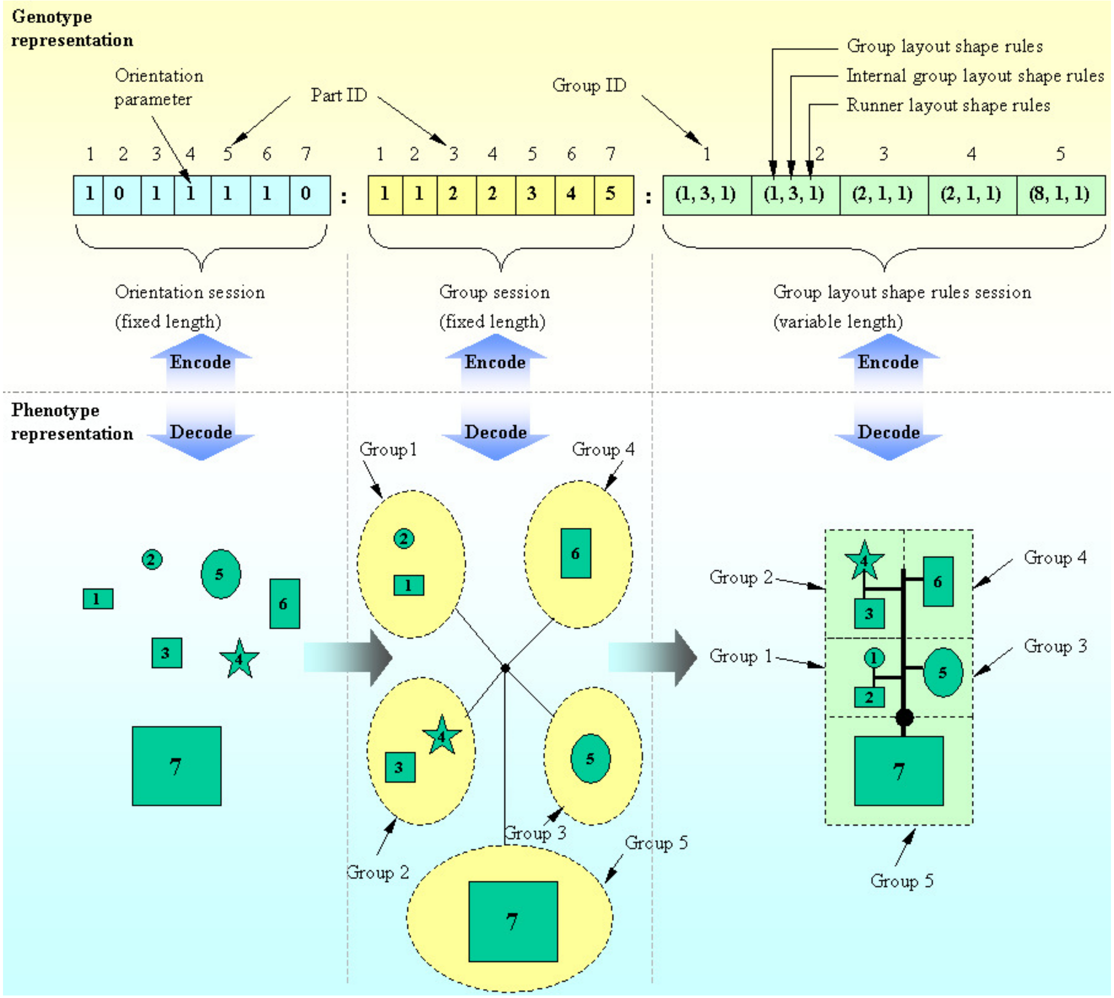

Figure 20. Genotype and phenotype representations of FMCRLD

4.3.3 New genetic operator design

As mentioned in Section 4.2, designing specific genetic operators that fit the properties of the new variable-length SG-based chromosome well is full of challenges. In this research, a new crossover operator and a new mutation operator were developed to reproduce valid offspring that can inherit meaningful "building blocks" from both parents.

(a) Crossover operator[*]

A new crossover operator combines the concept of the group-oriented crossover method of Group Genetic Algorithm (GGA) [173] and integrates with the SG of FMCRLD to reproduce valid offspring during the evolutionary process. As shown in Figures 21a and 21b, the first step is to select at random a crossing group in the *Group Layout Shape Rules Session* in each of the two parents with a predefined crossover rate.[†] As shown in the "Inject genetic contents" in Figure

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[*] *A more detailed description of the crossover operator design can be found in Chapter 7 of the 3rd portfolio submission – Automation and optimisation of FMCRLD using Shape Grammar and Genetic Algorithm*

[†] *Crossover rate is used to control the proportion of the number of crossing groups to the total number of cavity groups of the individual. For example, if the crossover rate is set to 0.3, the number of crossing groups for P1 and P9 will be equal to 0.3 x 3 = 0.9 (corrected to an integer value of 1) and 0.3 x 4 = 1.2 (corrected to an integer value of 2) respectively.*

21c and 21d, the second step is to inject the crossing groups of both parents to each other. The allele in the orientation session and the group session associated with the crossing section of the second parent (P9) are copied to the corresponding locus of the first parent (P1), and vice versa. The last step is to eliminate all objects occurring twice and empty cavity groups (see Figures 21e and 21f). Accordingly, the slider will also be automatically changed based on the new location and orientation of the parts in the new FMCRLD. Because of the SG of FMCRLD, the group layout design, the internal cavity layout design and the runner layout design of the new offspring can be intelligently regenerated while maintaining the feasibility of FMCRLD after the crossover operation (see Figures 21g and 21h). It is noticed that offspring C1 inherits the single slider design for Parts 2 and 3 from P1. Offspring C2 can inherit not only the single slider design for Parts 2 and 3 from P9 but also the balanced runner layout design from P1. This new group-oriented SG-based crossover operator can inherit or combine meaningful features from both parents to reproduce a stronger offspring without violation of the design constraints and disruption of the useful parts (schemata) of the chromosome during recombination.

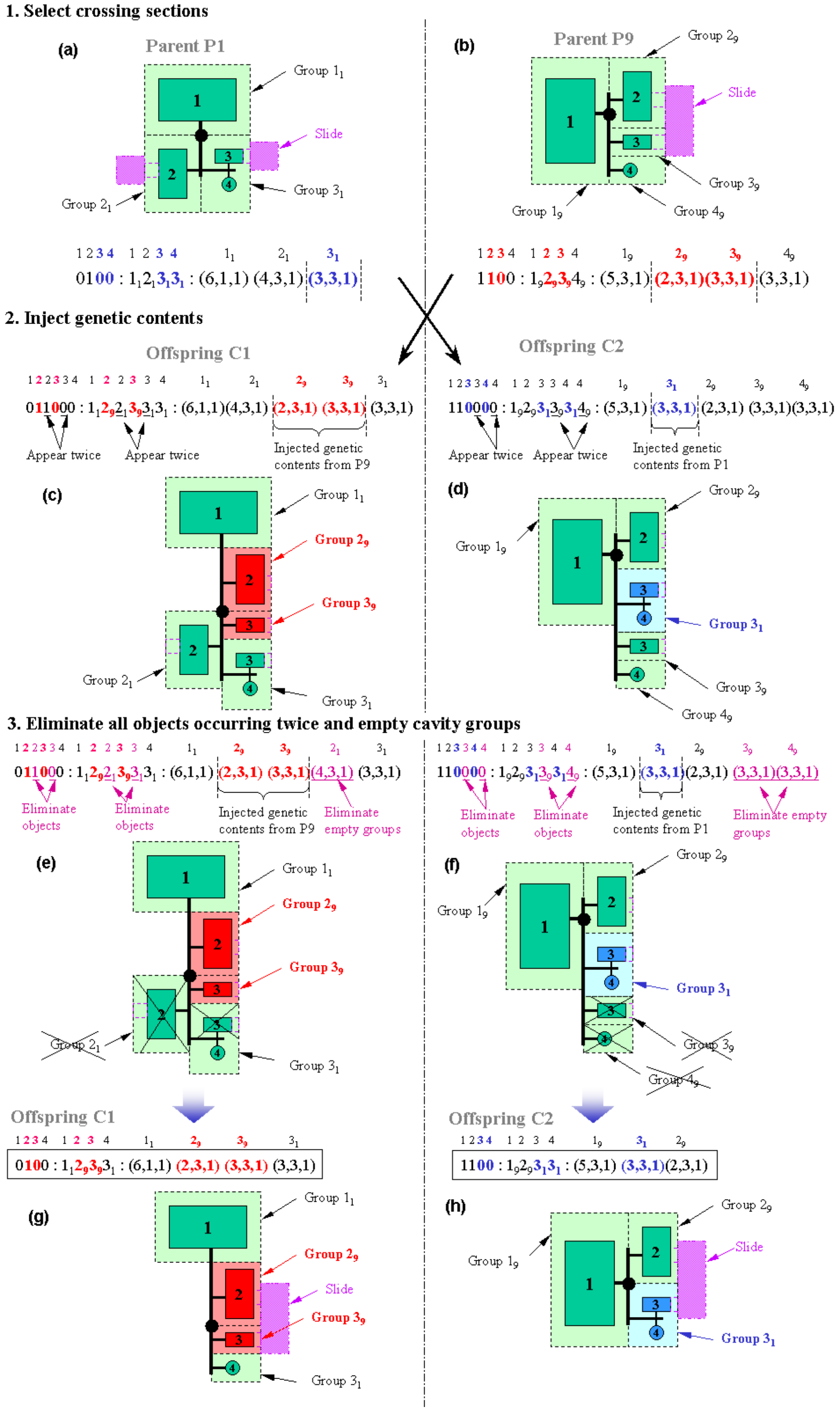

Figure 21. The group-oriented SG-based crossover approach

(b) Mutation operator[*]

A mutation operator aims to introduce new species into the population in the GA to explore the solution space by performing random modification of an individual's gene value. This research has developed three types of mutation operators for the (i) orientation session, (ii) group session, or (iii) group layout shape rules session of the new hybrid SG-based chromosome. One of these mutation operators for different sessions is selected at random and is applied to the offspring based on a predetermined mutation probability (mutation rate). Figure 22 illustrates the mutation operation occurring in the orientation session. One gene is selected at random. If there is no violation of the design constraints,[†] the allele of the selected gene will be flipped. If mutation takes place in the group session, there will be two options: modification of an existing group or creation of a new group. The first option aims to change the allele of the randomly selected gene in the group session at random and eliminate the empty group, if any (see Figure 23). The second option aims to create a new group. As illustrated in Figure 24, the first step is to create a new group at

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[*] *A more detailed description of the mutation operator design can be found in Chapter 8 of the 3rd portfolio submission – Automation and optimisation of FMCRLD using Shape Grammar and Genetic Algorithm*

[†] *The design constraints involve the allowable gate location of the part, existing runner layout and the space for the slider*

random in the group layout shape rules session. Then, the next step is to select a gene in the group session at random and change the allele (the group number) to the new group number. If the mutation operation occurs in the group layout shape rules session, then one allele in this session will be selected and modified at random. As shown in Figure 25, the phenotype can be changed accordingly. These three mutation operators integrated with the SG of FMCRLD can introduce new and feasible solutions into the population without violation of the design constraints.

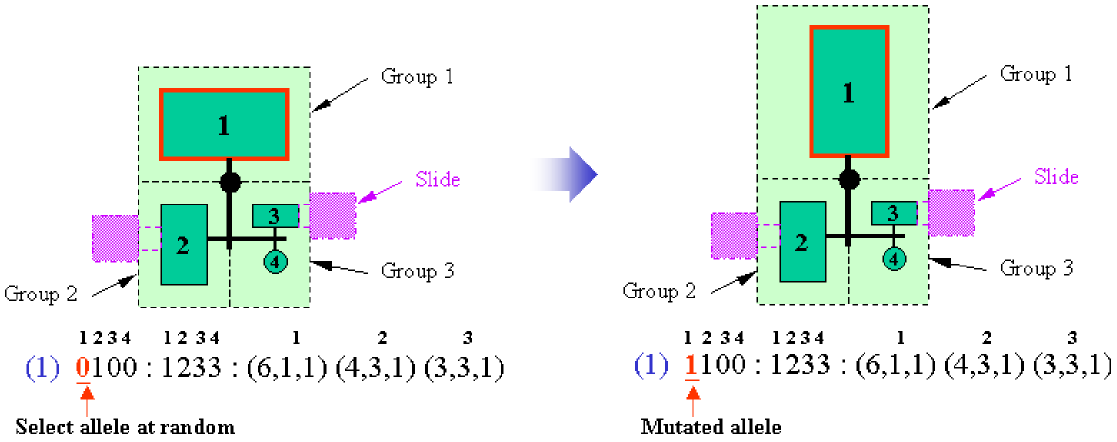

Figure 22. Mutation of the allele of the gene in the orientation session

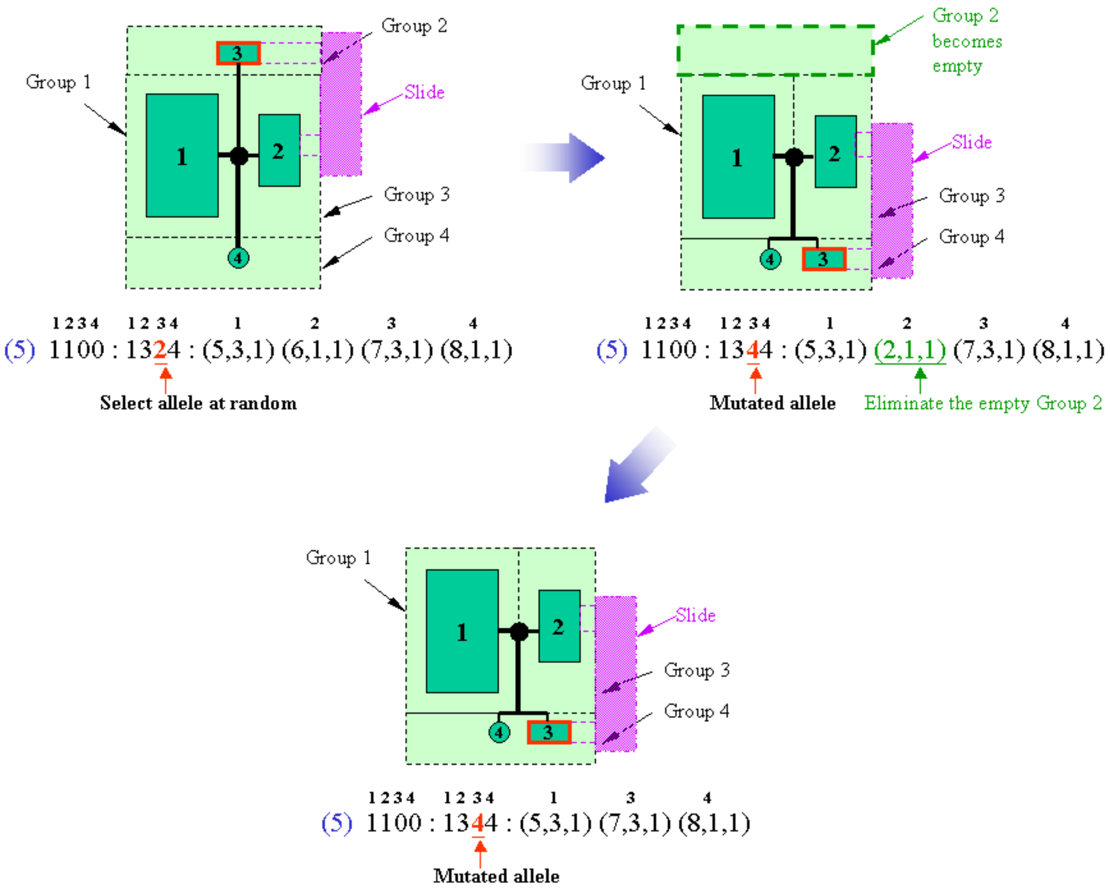

Figure 23. Mutation of the allele of the gene in the group session – change group and eliminate empty groups

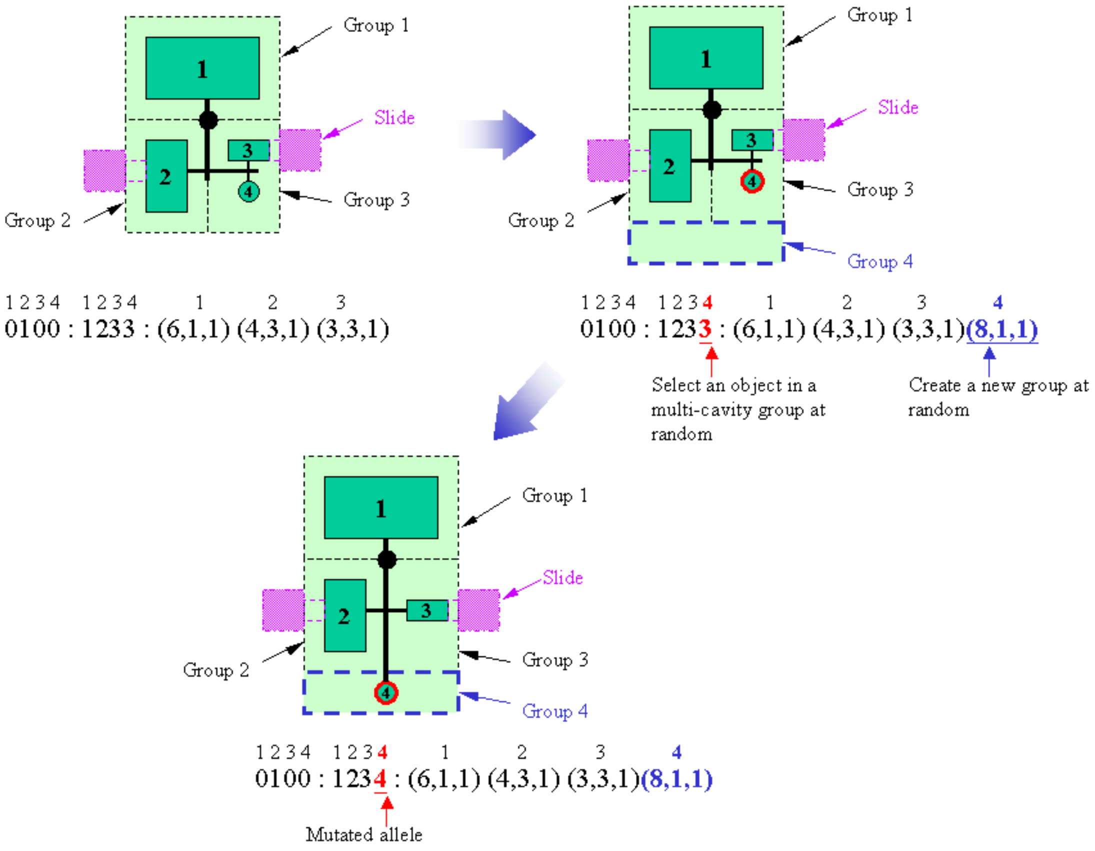

Figure 24. Mutation of the allele of the gene in the group session – create a new group

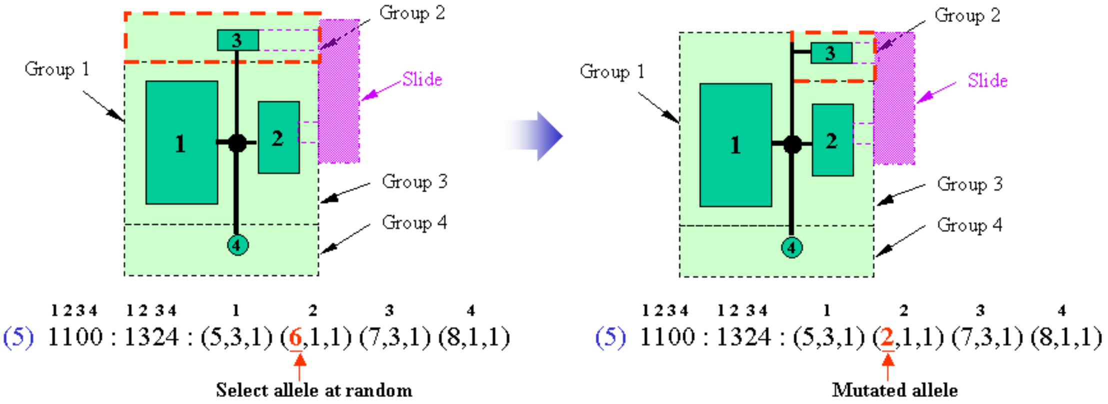

Figure 25. Mutation of the allele of the gene in the group layout shape rules session

4.3.4 New fitness evaluation methods for FMCRLD

In the GA, a fitness function should correlate closely with an objective function that quantifies the optimality of a solution [116]. In addition, the GA relies on a large number of fitness evaluations to converge to optimum solutions [116]. Therefore, the fitness function must be computed quickly. According to the multiple optimisation objectives as mentioned in Section 3.1.1, the evaluation criteria for optimum FMCRLD are mainly related to Cost (C) and Performance (P).

In this research, the quantitative cost evaluation[*] of FMCRLD focused on estimating the critical cost factors: Cost of mould insert (C_n), Cost of mould base (C_m), Cost of runners (C_r), Cost of external sliders (C_s) and Cost of injection moulding (C_j) using various empirical formulae developed based on experience (see Appendix A). These critical cost factors are directly driven by FMCRLD. The overall size of a cavity layout design determines the material cost of mould inserts and also the cost of its suitable mould base. The goal of reducing scrap plastic material is measured by calculating the total volume of runners. If some moulding parts have undercuts, the cost of sliders must be considered. The cost of sliders is estimated based on the

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[*] *A more detailed description of the cost evaluation of FMCRLD can be found in Section 4.1 of the 3rd portfolio submission – Automation and optimisation of FMCRLD using Shape Grammar and Genetic Algorithm*

required number and overall size of sliders. The maximum allowable mould based size is limited to the space between tie bars on the mould platen of a customer's available moulding machines. Therefore, different FMCRLD alternatives require different sizes of mould bases that affect the selection of injection moulding machines. The estimated cost of injection moulding depends on the total number of shots, the cycle time per shot and the average operating cost of the required injection moulding machine. In practice, a larger moulding machine requires a higher operating cost because of the higher purchase price, higher maintenance cost, higher energy consumption, more man-hours to set up and so forth.

With regard to the performance evaluation of FMCRLD,[*] filling balance is one of the most important performance goals in family mould design. As discussed in Section 3.1.2, it is too costly and time-consuming to use such expensive mould flow CAE simulation programs to evaluate a large number of combinations of different FMCRLD alternatives in the early design phase. Besides, filling balance performance evaluation of FMCRLD still requires an experienced engineer to correctly diagnose it based on the information provided by the simulation tool. In order to overcome this challenge, this research newly developed Flow path balance

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[*] *A more detailed description of performance evaluation of FMCRLD can be found in Section 4.2 of the 3rd portfolio submission – Automation and optimisation of FMCRLD using Shape Grammar and Genetic Algorithm*

performance measurement (P_f) and Runner diameter balance performance measurement (P_r) to quantify the filling balance performance of FMCRLD without the aid of expensive and time-consuming mould flow CAE simulation. In addition to the filling balance performance measurement, this research also developed new methods for quantifying Clamping force balance performance measurement (P_c) and Drop balance performance measurement (P_d).

(a) Flow path balance performance evaluation (P_f)

In order to achieve filling balance in a family mould, the pressure drop in each flow branch should be balanced with a proper cavity layout, runner lengths and diameters [5]. Existing commercial mould flow CAE packages [36, 37] can provide automatic artificial filling balance of a family mould by adjusting runner diameters based on a given FMCRLD only. However, it is very important to consider the effect of using different FMCRLD alternatives before performing artificial filling balance. This is because different runner layout alternatives result in distinct multiple flow groups with different flow lengths from the sprue to each cavity leading to different fill and pack pressure, flow rate, and the melt conditions within each cavity [7]. A "better" FMCRLD can improve the artificial filling balance performance with a wider process window. In this research, a Flow Path Balance Ratio (FPBR) was newly developed to measure the variation of flow lengths across all different flow paths of dissimilar cavities in a family mould (see Figure 26).

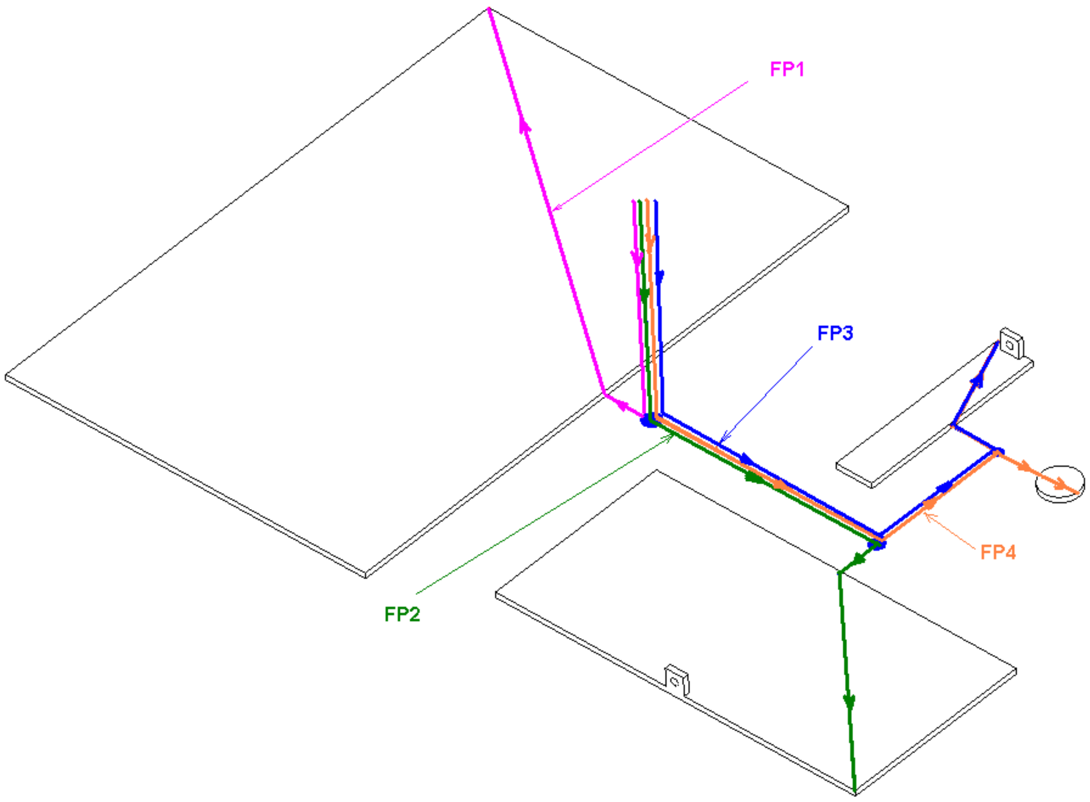

Figure 26. Illustrative examples of flow paths of four dissimilar cavities in a family mould.

This FPBR can quantify the filling balance performance of a large number of FMCRLD alternatives rapidly for fitness evaluation in GA without using time-consuming and computer-intensive mould flow CAE simulations to evaluate numerous different FMCRLD alternatives. The FPBR is defined as the average variation of Flow Path (FP) relative to the minimum FP across all flow groups (see Equation B.1.1 in Appendix B.1). The Flow Path (FP) of each individual flow group consists of its individual Runner Flow Path[*] (RFP) and its Cavity Flow Path[†] (CFP). The smaller the FPBR is the better the filling balance performance that can be achieved. If all FP across all flow groups are the same, FPBR will be equal to one in the ideal case for filling balance performance. This research first defined a Flow Path Balance Performance value (P_f) to measure the relative performance of an individual compared to the user-defined goal value of the FPBR (see Equation B.1.2 in Appendix B.1).

(b) Runner diameter balance performance evaluation (P_r)

The Flow Path Balance Ratio (FPBR) focuses on measuring the average variation of FP relative to the minimum FP across all flow groups, but it cannot consider the effect of possible flow hesitation caused by the significant variation

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[*] *RFP is the total length of various runner branches delivered from the sprue to the gate of the cavity.*

[†] *CFP is the estimated longest flow length measured from the selected gating location to the boundary of the cavity.*

of diameters of all runner segments.[*] As shown in Figure 27, different FMCRLD alternatives have different numbers of runner segments with different lengths and branching nodes resulting in different variations of the diameters of each runner segments.[†] In this research, a Runner Diameter Balance Ratio (RDBR) was developed to measure the variation of runner diameters at each runner branching node (see Equation B.2.1 in Appendix B.2). For example, RDBR at $J_{1,1}$ is equal to 1.22 ($R_{1,1}$ / $R_{1,2}$ = 5.5 / 4.5). RDBR at $J_{1,2}$ is equal to 1.33 ($R_{1,3}$ / $R_{1,4}$ = 4.0 / 3.0). RDBR at $J_{1,3}$ is equal to 1.25 ($R_{1,5}$ / $R_{1,6}$ = 2.5 / 2.0). The overall RDBR of FMCRLD solution (i) is defined as the maximum RDBR across all junctions (see Equation C2 in Appendix C). In this case, the overall RDBR is less than two. This means that this FMCRLD has a better chance of avoiding possible flow hesitation occurring at runner branching nodes. This research first defined a Runner Diameter Balance Performance value (P_r) to measure the relative performance of an individual compared to the user-defined goal value of the Runner Diameter Balance Ratio (RDBR) (see Equation B.2.2 in Appendix B.2).

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[*] *From experience, if the ratio of the maximum runner diameter to the minimum one at a branching node exceeds two, it may result in flow hesitation at this branching node.*

[†] *In practice, varying diameter runners are commonly used to reduce either the filling pressure or the amount of plastic material consumption. The diameter of each successive branch is calculated from the gate back to the sprue using the empirical formulae (see Appendix B).*

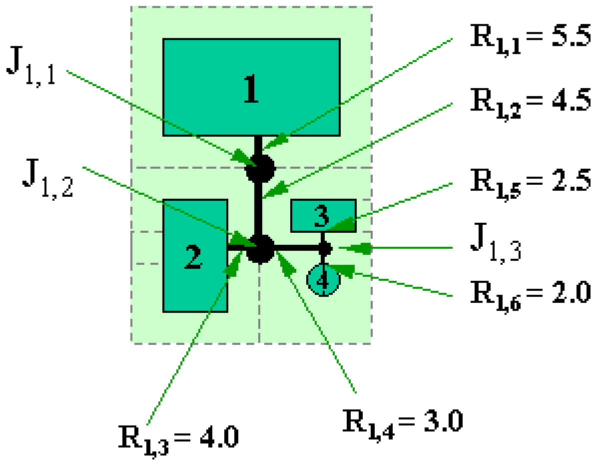

Figure 27. Runner Diameter Balance Ratio (RDBR) illustrative example

(c) Clamping force balance performance evaluation (P_c)

As mentioned in Section 3.1.1, cavities should be arranged about the centre of the mould as symmetrically as possible to ensure an even and adequate clamping force over the entire mould area. This research made use of the centre of the resultant clamping force acting on all dissimilar parts located in different locations with respect to the centre of a family mould to measure the clamping force balance performance of a FMCRLD alternative (as calculated using Equations B.3.1 and B.3.2 in Appendix B.3). As shown in Figure 28, the offset dimension (d) is defined as the offset distance between the centre of the resultant clamping force and the centre of the family mould for the given cavity layout design (as calculated using Equation B.3.3 in Appendix B.3). The smaller the offset dimension (d) is the better clamping force balance performance that can be achieved. This research defined a clamping force balance performance value (P_c) to measure the relative performance of an individual compared to the user-defined goal value of the offset dimension (d) (see Equation B.3.4 in Appendix B.3).

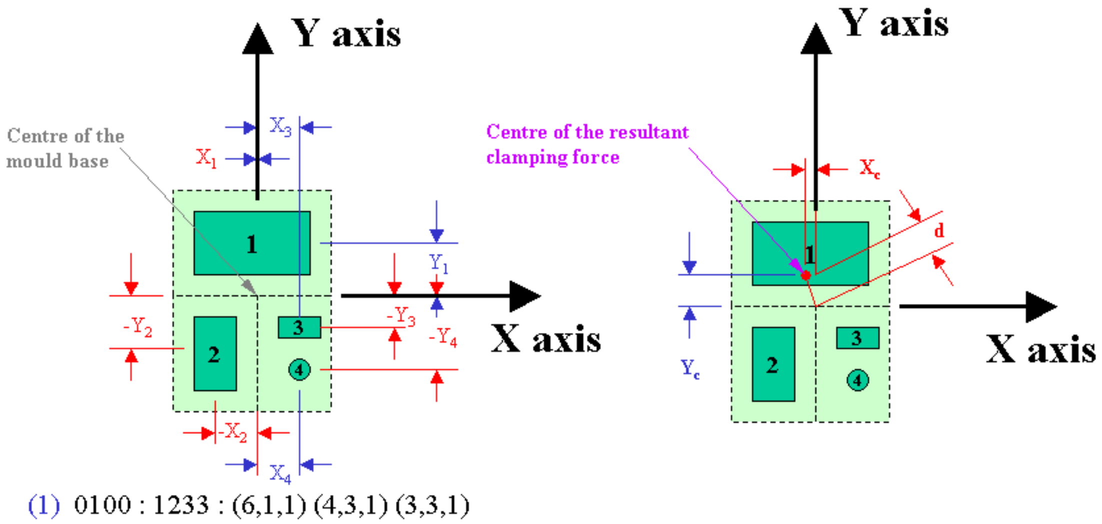

Figure 28. Centre of resultant clamping force of a family mould

(d) Drop time performance evaluation (P_d)

As shown in Figure 29, FMCRLD affects the drop height (h_i) of the moulding parts. Assuming that the product has no initial speed downward at the point of ejection, the estimated drop time can be calculated using Equation B.4.1 as shown in Appendix B.4. Accordingly, the drop time performance value (P_d) was defined to measure the relative performance of an individual compared to the user-defined goal value of the drop time (see Equation B.4.2 in Appendix B.4).

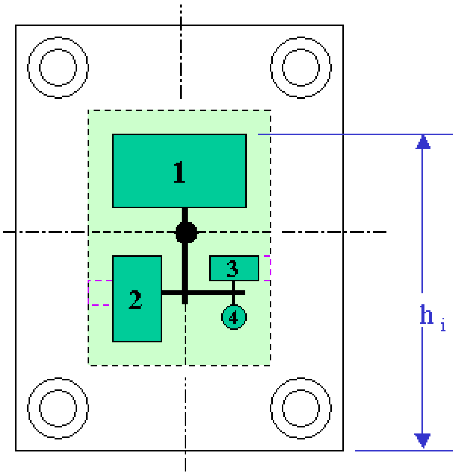

Figure 29. Drop height of moulding parts of a family mould

4.4 Implementation of evolutionary FMCRLD

This section aims to summarise how to implement the innovative evolutionary FMCRLD approach in this research. The system development of ICMLDS is presented in Section 4.4.1. The core of the whole system – Evolutionary FMCRLD using Shape Grammar (SG) and Genetic Algorithm (GA) is briefly described in Section 4.4.2.

4.4.1 ICMLDS prototype

In this research, an innovative ICMLDS prototype seamlessly integrated with the ProEngineer® Wildfire™ 4.0 MCAD system was developed using ProToolKit® Application Programming Interface (API) [174] for ProEngineer® Wildfire™ 4.0 (Datecode M170) and Microsoft® Visual Studio® C/C++ 2005 based on Microsoft® Windows XP ® (64 bit) operation system platform running on a Personal Computer (PC) workstation.[*] This ICMLDS prototype is an advanced evolutionary design tool for supporting FMCRLD automation and optimisation in the early quotation phase

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[*] *The ICMLDS prototype was running on an HP™ xw6200 workstation equipped with a dual Intel® Xeon™ CPU of 3.0GHz, 4GB of DDR2 RAM and Nvidia® Quadro™ FX1400 graphic card.*

and CMLD phase. It aims to accelerate mould designers' design alternative exploration, exploitation and optimisation for better design in less time. Figure 30 illustrates the system architecture of the ICMLDS prototype. Mould designers are required to input information of part models, moulding requirements and constraints using the user input interface module[*] embedded within the MCAD system. The evolutionary FMCRLD module is the core of the whole system that generates FMCRLD automatically and searches for optimum solutions using Shape Grammar (SG) and Genetic Algorithm (GA) (see Section 4.4.2). The system output interface module[†] is used to provide rapid visualisation and display fitness evaluation results of different FMCRLD alternatives in the resulting population generated from the evolutionary FMCRLD module. Based on mould designers' final design decisions, the system output module can generate mould layout design CAD models and associated layout drawings accordingly using the mould design CAD model library and the customised mould layout CAD drawing template.

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[*] *Users are required to define the part information (such as parting direction, allowable gate locations, estimated CFP, sliding actions and so on), the moulding requirements (such as total number of shots and the estimated total cycle time) and the mould base size constraint (the maximum allowable mould base size). A more detailed description of the implementation of the user input interface module of the ICMLDS prototype can be found in Section 2.3 of the 4th portfolio submission – ICMLDS implementation and verification.*

[†] *A more detailed description of the implementation of the system output module of the ICMLDS prototype can be found in Section 2.5 of the 4th portfolio submission – ICMLDS implementation and verification.*

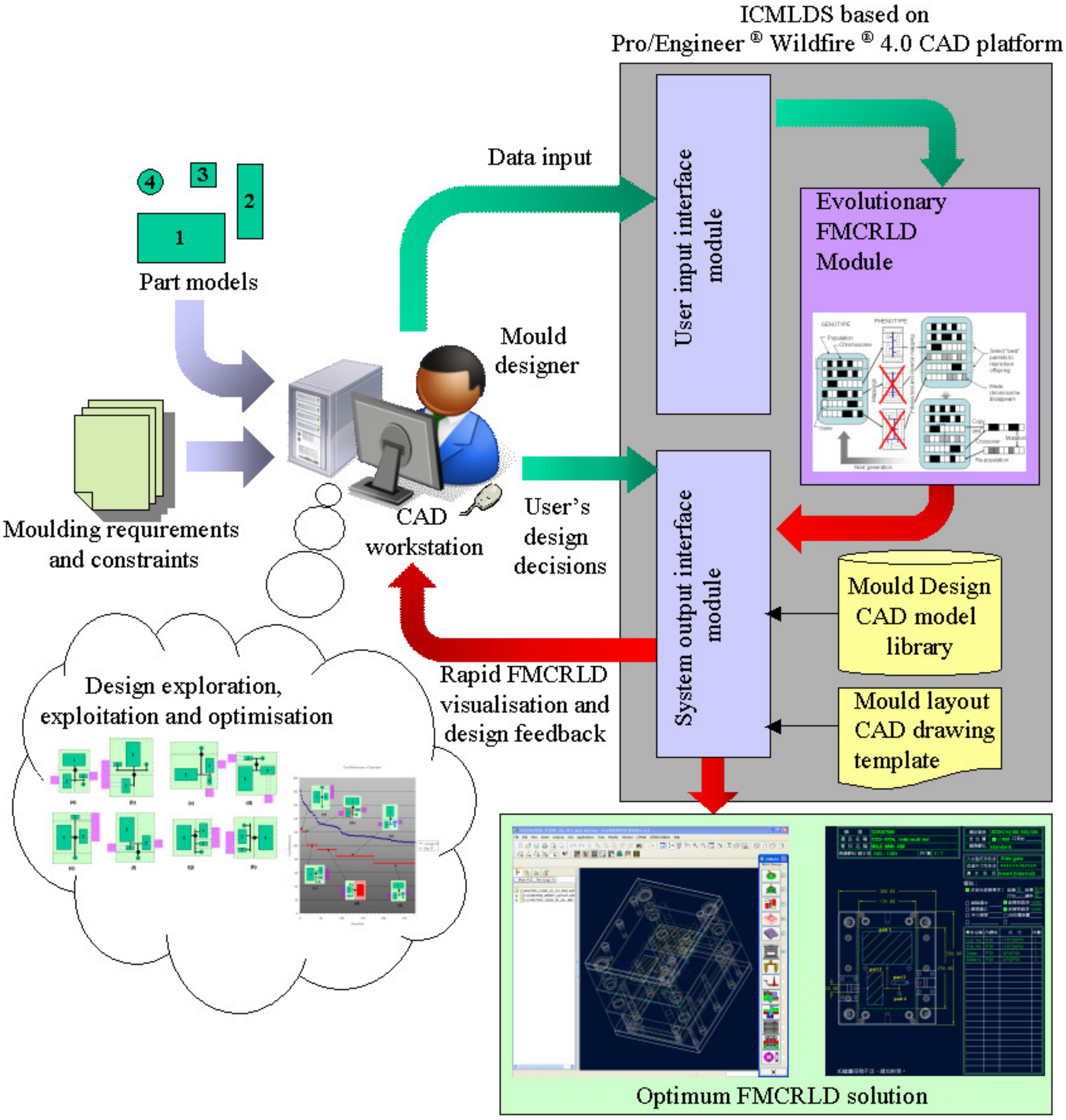

Figure 30. System architecture of the ICMLDS prototype

4.4.2 Evolutionary FMCRLD using Shape Grammar (SG) and Genetic Algorithm (GA)*

Based on the innovative approaches as described in Section 4.3, an evolutionary FMCRLD module of the ICMLDS was successfully developed. This module consists of two main components: Shape Grammar (SG) module and Steady-State Genetic Algorithm (SSGA) module. Figure 31 illustrates the program flow chart of this important module. According to the system input information, the algorithm (starting from steps 1.1 to 1.6) integrated with the SG of FMCRLD and mould design knowledge was developed to generate valid chromosomes of individuals in the initial population (P) step by step (see Appendix C). The algorithm will stop when the number of generated individual design solutions is equal to the specified population size 'm'. Meanwhile, the generation counter (i) is set to one initially. At step (2), the Genotype-Phenotype mapping algorithm denoted as step (3) is called to decode the chromosome into the phenotype for fitness evaluation. As shown in Figure 32, the mapping algorithm starts from reading the chromosome data at step 3.1. At step 3.2, the data of each part(i), such as its size, wall thickness, CFP and so on, is read

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* *A more detailed description of the evolutionary FMCRLD module of the ICMLDS prototype can be found in Section 24 of the 4th portfolio submission – ICMLDS implementation and verification*

from the corresponding pointer arrays[*] stored in the system memory. Step 3.3 is to count the total number of groups (n) in the group layout shape rule session. Then, a program loop is started from steps 3.4 to 3.7 for each group. The order of all parts in a group according to their projected area is ranked in step 3.4. Step 3.5 is to calculate the assembly coordinates of parts in each group according to the layout position decoded from the internal group layout SG rule number. At step 3.6, the assembly coordinate of each group is calculated according to its overall size and the layout position decoded from the group layout SG rule number. Step 3.7 is to create runner segments connecting the gates of all parts in each group to the sprue according to the runner layout design decoded from the runner layout SG rule number. At step 3.8, the smallest suitable mould base is selected from the standard mould base database based on the condition: if the width of the mould insert (I_x) is equal to or smaller than the width of the ejector plate of the mould base (M_x) and the length of the mould insert (I_y) is equal to or smaller than the inner vertical space between the return pins (M_y). Step 3.9 is to calculate the diameter of each runner segment according to the empirical formula (see Appendix D.1) in relation to W_i, L_i, T_i and the number of runner branches. With regard to the generation of sliders, the program loop is started from steps 3.10 to 3.11 for four sides of the mould. At step 3.10, if the number of

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[*] *Pointer array enables Pro/Toolkit applications to allocate an array of any object with no preset limits on its size. More detailed descriptions of "ProArray" can be found in the literature [174].*

sliders on each side is more than one, all the sliders will be grouped into one slider. Step 3.11 is to complete the slider design on each side according to the empirical slider design rules (see Appendix D.2). Finally, the resulting phenotype will be saved in the pointer arrays at step 3.12. According to the resulting phenotype, the fitness value of each individual in the population can be calculated using the weighted sum approach. This simple approach can integrate a number of performance goals (P_f, P_r, P_c and P_d), costs (C_m, C_n, C_r, C_s and C_j) and the penalty function for handling the mould base size constraint into a single Cost Performance (CP) value (see Appendix E). This approach allows mould designers to change the priority of individual performance goal, cost and the penalty function for different mould customers' specifications and requirements in a simple way.

In this research, an overlapping steady-state population model was adopted in an attempt to reduce the computing workload as well as the memory usage for the fitness evaluations and the genetic operations. In this model, offspring and parents in the same population compete for survival. The number of individual in the population to be replaced during each generation is controlled by the generation gap (G). Starting from steps 4 to 14, the main program loop begins. Initially, the generation gap counter g is set to one. At step 5, two parents from the population (P) are selected at random using a tournament selection strategy.* This selection strategy can simulate the mating battles often seen in nature by mutual "competition" of *s* individuals (tournament size) chosen at random from the population. In other words, it can provide the stochastic "ingredient" of the selection naturally introduced by the random choice of competing couples [173]. At step 6, a new offspring is reproduced using the new crossover operation with a predefined crossover rate (see Section 4.3.3). Subsequently, the offspring is mutated at step 7 using the new mutation operation with a predefined mutation rate (see section 4.3.3). At step 8, the fitness of the new offspring is evaluated. This research adopted a simple Replace the Worst (RW) replacement strategy because it can imitate the natural evolutionary process of "Survival of the Fittest" in the simplest way. If the fitness of the new offspring is better than the worst individual found in the population (P), then this worst individual will be replaced by this new offspring. Accordingly, the overlapping population (P) is updated at step 10. At step 11, if the generation gap counter *g* is equal to the generation gap (G), then the program will check if one of the stopping criteria, which include the maximum number of generations,† maximum running time‡ and stall

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* *A detailed description of the tournament selection strategy used in this research can be found in Section 6.3 of the 3rd portfolio submission – Automation and optimisation of FMCRLD using Shape Grammar (SG) and Genetic Algorithm (GA)*

† *Maximum number of generations – The algorithm stops when the predefined maximum number of generations is reached.*

‡ *Maximum running time – The algorithm stops when the predefined maximum allowable running time is reached.*

generations,[*] is met, or else the program will go to step 12 to accumulate the generation gap counter *g* by 1, and go back to step 5. When the generation gap counter *g* is equal to the generation gap G, the program checks the stopping criteria again at step 13. If one of the termination criteria is met, the program will pass the resulting population (P) to the system output interface module, or else the generation counter *i* will be accumulated by 1 at step 14 and the program will go back to step 4 to start the next program loop for the next generation. These stopping criteria are used to prevent the GA from running for too long. If the result is not satisfactory when the algorithm stops due to one of these conditions, the values of Maximum running time and Stall generations can be increased to improve the results.

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[*] *Stall generations – The algorithm stops if there is no improvement in the CP value for a sequence of a predefined number of generations.*

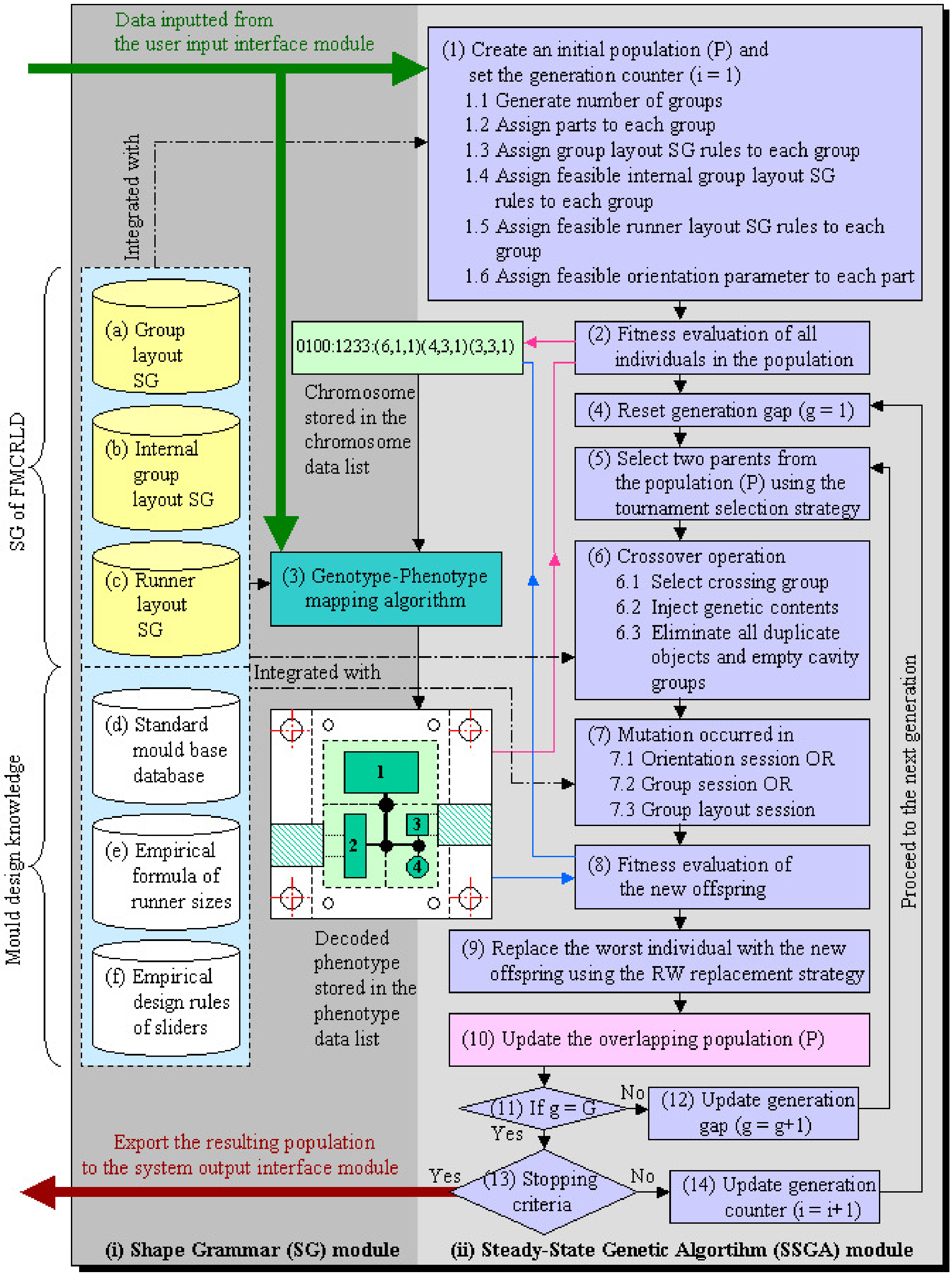


Figure 31. The program flow chart of the evolutionary FMCRLD module

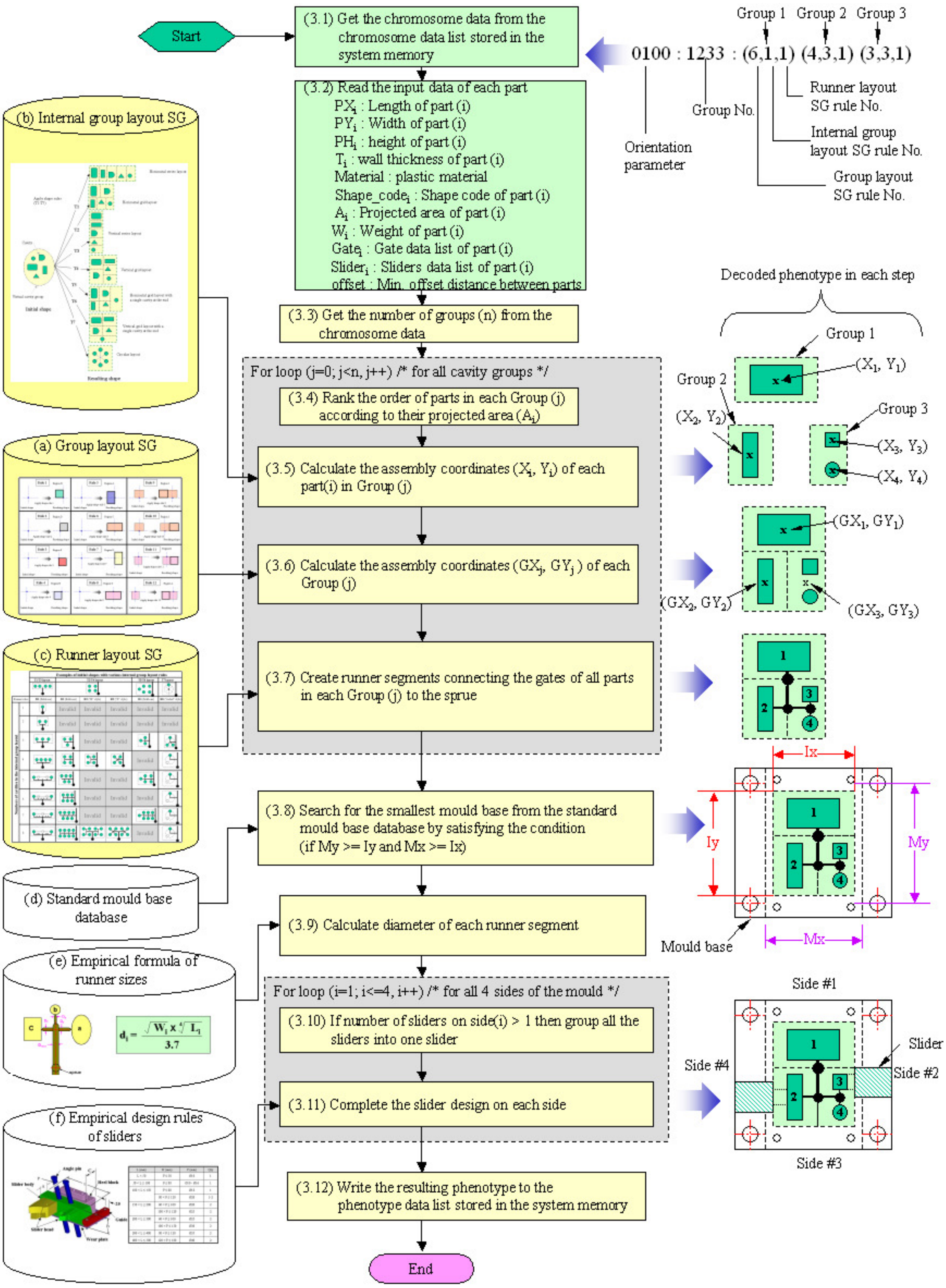


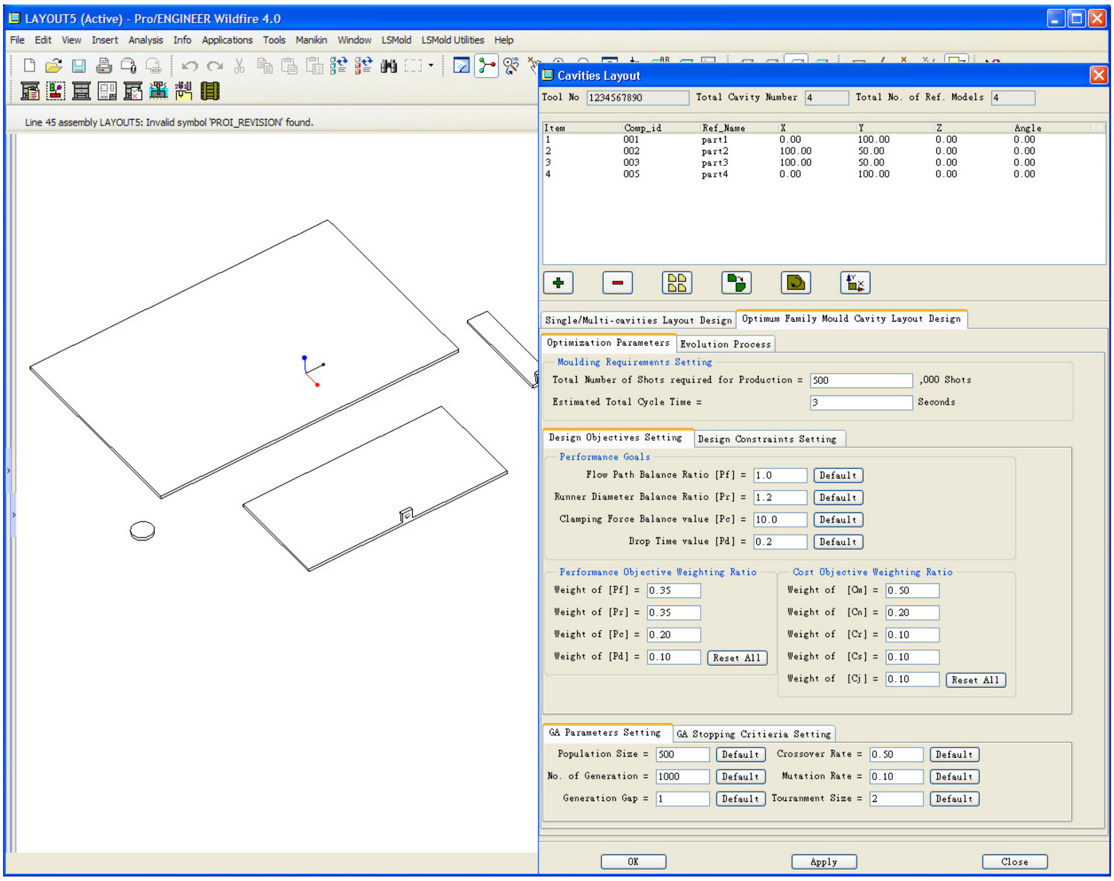
Figure 32. The program flow chart of the Genotype-Phenotype mapping algorithm

5 RESEARCH RESULTS

In this research, three case studies were examined to verify the evolutionary FMCRLD approach and demonstrate how the ICMLDS prototype can automate and optimise FMCRLD in practice. First of all, an experimental case study and the system output are described in Section 5.1. Subsequently, verification and analysis of the experimental results are discussed in Section 5.2. Two implementation examples are presented in Section 5.3. Achievement of this ICMLDS prototype are summarised in Section 5.4. Finally, the limitations of this research and suggestions for further work are discussed in Section 5.5.

5.1 Experimental case study

In this experimental case study, four parts varying from 0.12 grams to 23.49 grams are required to be moulded in ABS (Polylac PA-757) in one shot with a family mould. The detailed drawings of Parts 1-4 are shown in Figure F1.1-F1.4 in Appendix F.1. The specification of the parts is summarised in Table F2.1 in Appendix F.2. Through the use of the graphical user interface seamlessly embedded into the commercial CAD system, four dissimilar parts are initially added into the ICMLDS (see Figure 33).



Line 45 assembly LAYOUT5: Invalid symbol 'PROI_REVISION' found.

Tool No 1234567890 Total Cavity Number 4 Total No. of Ref. Models 4

Item	Comp_id	Ref_Name	X	Y	Z	Angle
1	001	part1	0.00	100.00	0.00	0.00
2	002	part2	100.00	50.00	0.00	0.00
3	003	part3	100.00	50.00	0.00	0.00
4	005	part4	0.00	100.00	0.00	0.00

Moulding Requirements Setting

Total Number of Shots required for Production = 500 ,000 Shots

Estimated Total Cycle Time = 3 Seconds

Performance Goals

Flow Path Balance Ratio [Pf] = 1.0 Default

Runner Diameter Balance Ratio [Pr] = 1.2 Default

Clamping Force Balance value [Pc] = 10.0 Default

Drop Time value [Pd] = 0.2 Default

Performance Objective Weighting Ratio

Weight of [Pf] = 0.35

Weight of [Pr] = 0.35

Weight of [Pc] = 0.20

Weight of [Pd] = 0.10 Reset All

Cost Objective Weighting Ratio

Weight of [Cm] = 0.50

Weight of [Cn] = 0.20

Weight of [Cr] = 0.10

Weight of [Cs] = 0.10

Weight of [Cj] = 0.10 Reset All

Population Size = 500 Default Crossover Rate = 0.50 Default

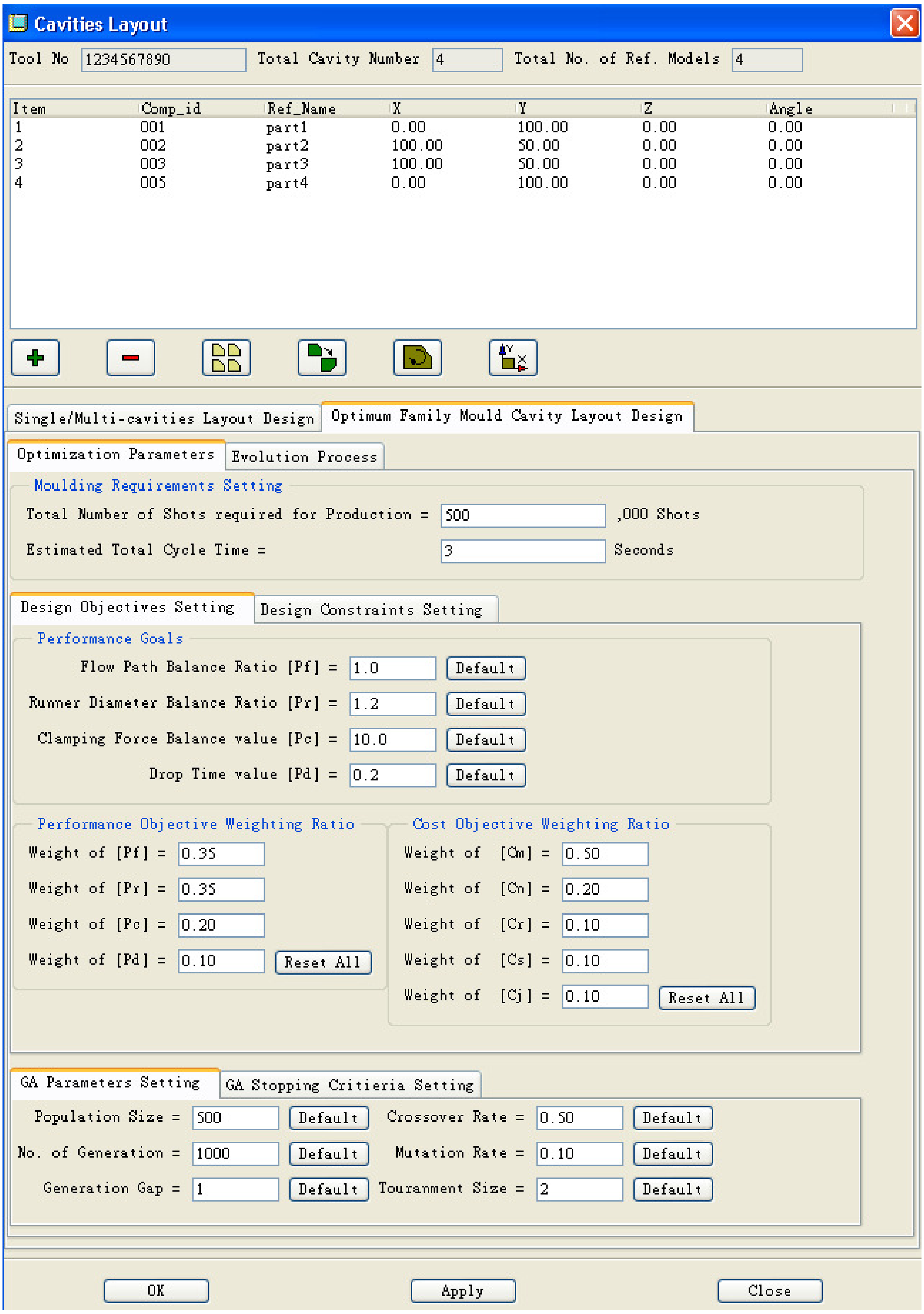
No. of Generation = 1000 Default Mutation Rate = 0.10 Default

Generation Gap = 1 Default Tournament Size = 2 Default

Figure 33. The screen capture of the graphical user interface of the FMCRLD prototype system integrated with the ProEngineer® Wildfire ™ 4.0

Then users can change the moulding requirements, the parameters of design objectives and GA parameters for different design cases (see Figure 34). In this experiment, the total number of shots was set to 500,000 and the total cycle time was estimated to be 3 seconds. It is difficult to design a good FMCRLD for dissimilar parts having such significant variations in sizes. In an attempt to search for optimum

FMCRLD solutions with good filling balance performance and the use of smaller mould bases, the weighting ratios of P_f, P_r and C_m were set to be higher than others for this experiment. Through the use of the user input interface as shown in Figure 35, users can specify the mould base size constraint and the stopping criteria if necessary. The setting of design objectives and constraints used in this example is summarised in Table F.3.1 in Appendix F3. As discussed in section 3.2.2, the performance of the GA depends on the choice of GA parameters. One of the most important parameters is the population size [175]. If the population size is too small, the GA may not explore enough of the solution space to consistently find good solutions leading to a premature convergence problem. The larger the population sizes, the greater the chance that the GA can find global optimum solutions because of its more diverse gene pool. However, a very large population would be computationally expensive. There should be an optimum value in between, but finding an optimum setting of GA parameters is problem-specific and outside the scope of this research. This research focused more on accelerating mould designers' design alternative exploration, exploitation and optimisation for better design in less time. In an attempt to provide a more diverse gene pool for the GA to explore and exploit more design alternatives to search for global optimum solutions in a limited time, a reasonably large population of about 500 was chosen for this experimental first try. The setting of all the GA parameters used in this experiment is listed in Table F.3.2 in Appendix F3. If necessary, the GA parameters may need to be adjusted according to the optimisation results. The program was repeated 5 times using the same setting and the best solution of the 5 runs was selected. Figure 36 shows the list of a number of feasible FMCRLD alternatives associated with their fitness values. Users can browse and visualise different FMCRLD alternatives in the population to select the best solution (see Figure 37). Figure 38 shows some FMCRLD alternatives, which were automatically evolved by the ICMLDS prototype. Finally, the prototype system automatically generated the 3D mould layout design model based on the selected FMCRLD for downstream detail mould design and manufacturing (see Figure 39). Accordingly, the 2D mould layout drawing associated with a table of BOM, mould design configuration and specification were also generated automatically, accurately and quickly (see Figure 40).



Tool No 1234567890
Total Cavity Number 4
Total No. of Ref. Models 4

Item	Comp_id	Ref_Name	X	Y	Z	Angle
1	001	part1	0.00	100.00	0.00	0.00
2	002	part2	100.00	50.00	0.00	0.00
3	003	part3	100.00	50.00	0.00	0.00
4	005	part4	0.00	100.00	0.00	0.00

Moulding Requirements Setting

Total Number of Shots required for Production = 500 ,000 Shots
Estimated Total Cycle Time = 3 Seconds

Performance Goals

Flow Path Balance Ratio [Pf] = 1.0
Runner Diameter Balance Ratio [Pr] = 1.2
Clamping Force Balance value [Pc] = 10.0
Drop Time value [Pd] = 0.2

Performance Objective Weighting Ratio

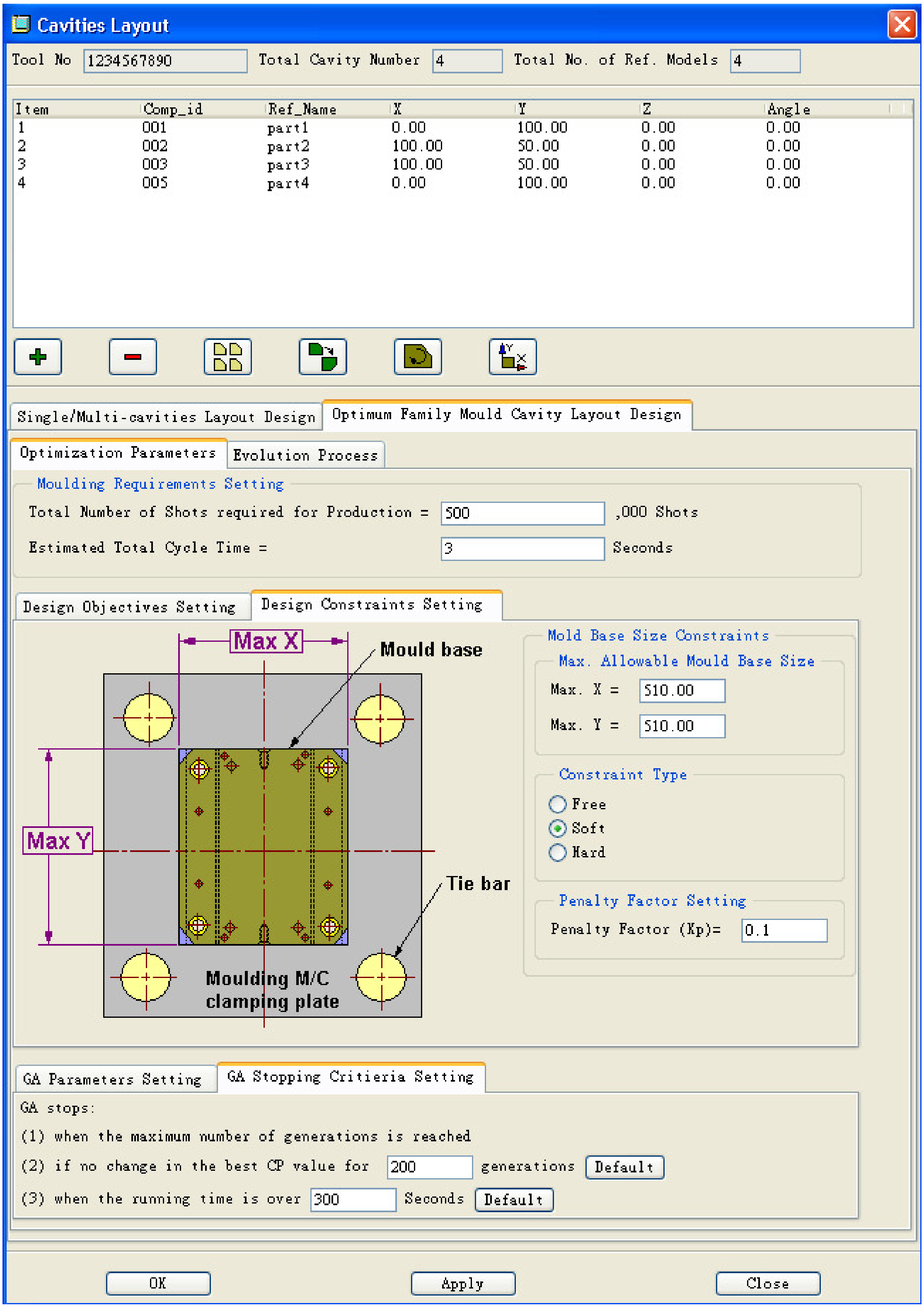
Weight of [Pf] = 0.35
Weight of [Pr] = 0.35
Weight of [Pc] = 0.20
Weight of [Pd] = 0.10

Cost Objective Weighting Ratio

Weight of [Cm] = 0.50
Weight of [Cn] = 0.20
Weight of [Cr] = 0.10
Weight of [Cs] = 0.10
Weight of [Cj] = 0.10

Population Size = 500
No. of Generation = 1000
Generation Gap = 1
Crossover Rate = 0.50
Mutation Rate = 0.10
Tournament Size = 2

Figure 34. The graphical user interface developed for inputting the parameters of moulding requirements, design objectives and GA



Cavities Layout

Tool No 1234567890 Total Cavity Number 4 Total No. of Ref. Models 4

Item	Comp_id	Ref_Name	X	Y	Z	Angle
1	001	part1	0.00	100.00	0.00	0.00
2	002	part2	100.00	50.00	0.00	0.00
3	003	part3	100.00	50.00	0.00	0.00
4	005	part4	0.00	100.00	0.00	0.00

Moulding Requirements Setting

Total Number of Shots required for Production = 500 ,000 Shots

Estimated Total Cycle Time = 3 Seconds

Mold Base Size Constraints

Max. Allowable Mould Base Size

Max. X = 510.00

Max. Y = 510.00

Constraint Type

○ Free
● Soft
○ Hard

Penalty Factor Setting

Penalty Factor (Kp)= 0.1

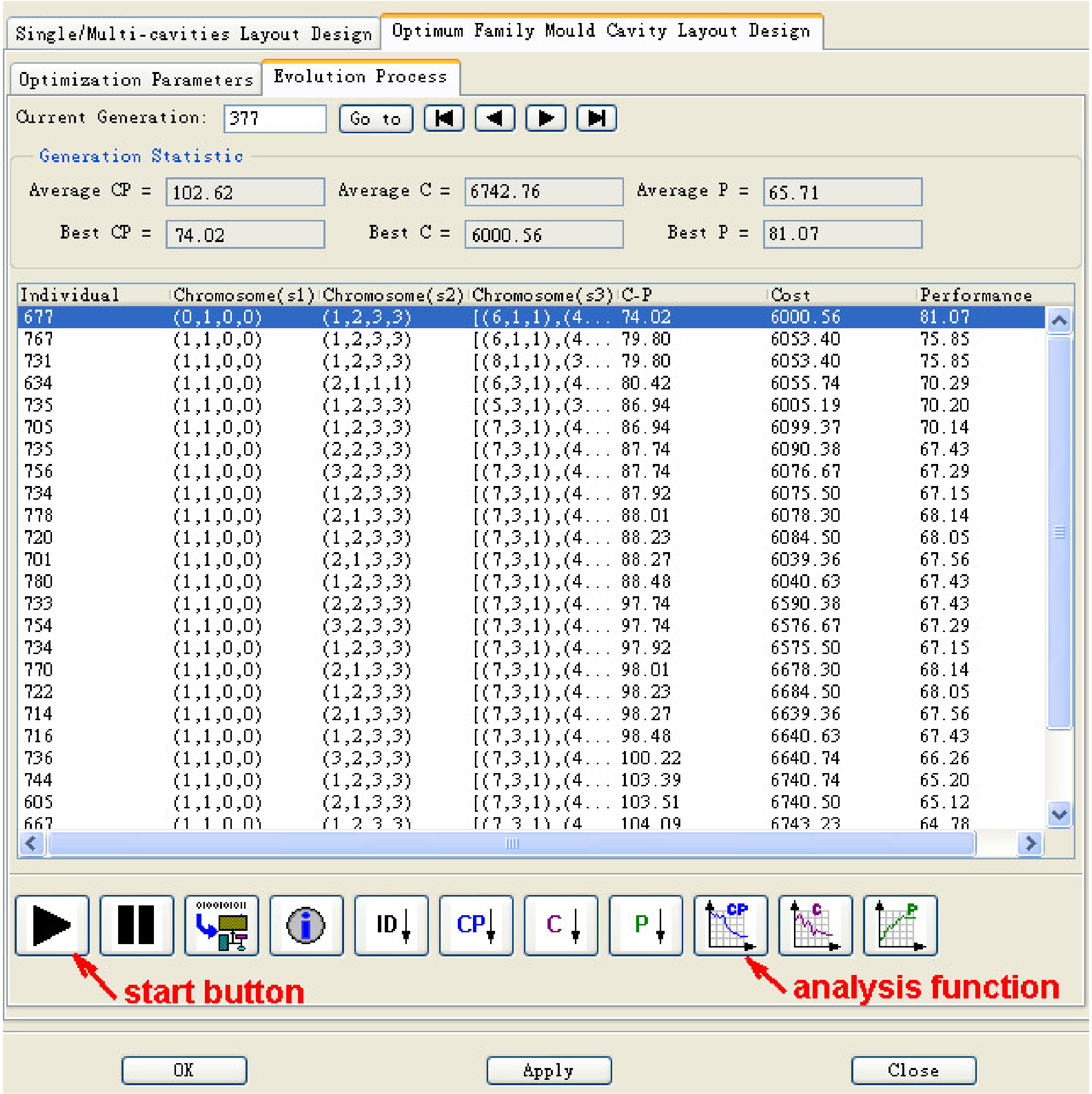
GA stops:

(1) when the maximum number of generations is reached

(2) if no change in the best CP value for 200 generations Default

(3) when the running time is over 300 Seconds Default

Figure 35. The graphical user interface developed for inputting the design constraints and the GA stopping criteria



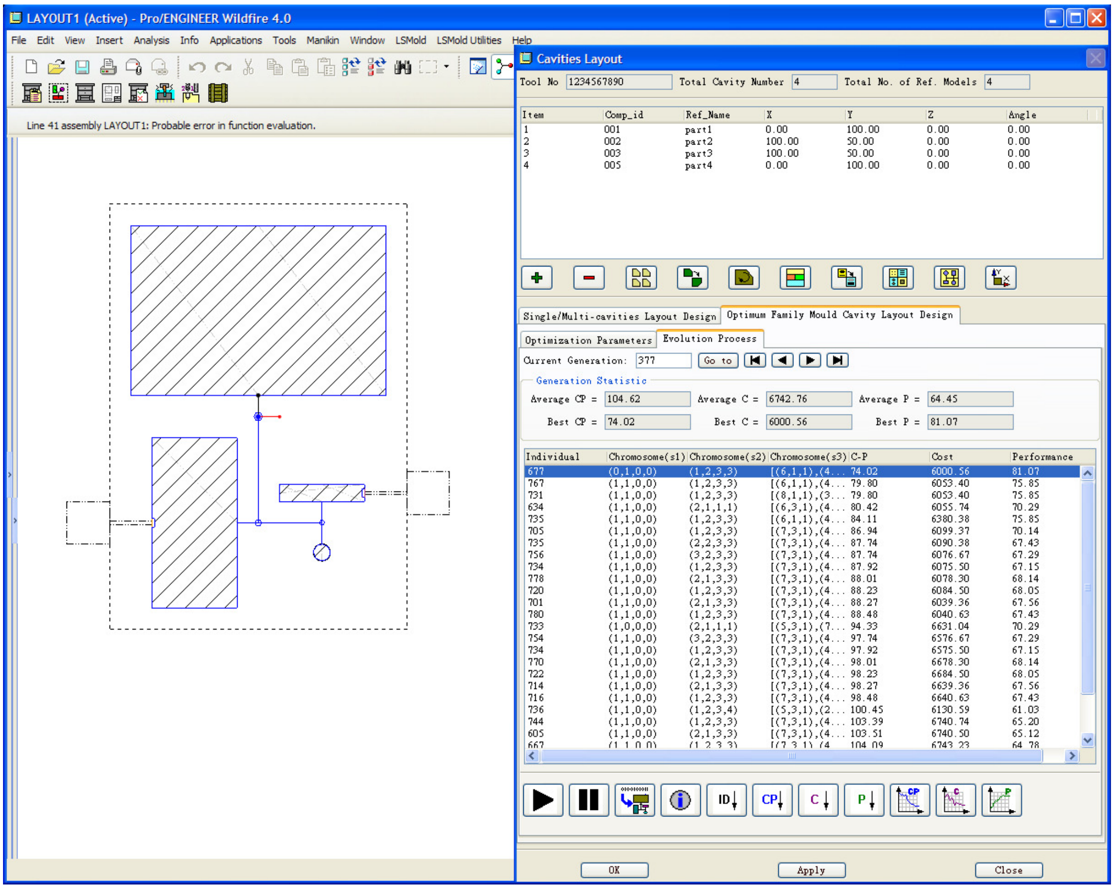
Current Generation: 377

Average CP = 102.62 Average C = 6742.76 Average P = 65.71

Best CP = 74.02 Best C = 6000.56 Best P = 81.07

Individual	Chromosome(s1)	Chromosome(s2)	Chromosome(s3)	C-P	Cost	Performance
677	(0,1,0,0)	(1,2,3,3)	[(6,1,1),(4...	74.02	6000.56	81.07
767	(1,1,0,0)	(1,2,3,3)	[(6,1,1),(4...	79.80	6053.40	75.85
731	(1,1,0,0)	(1,2,3,3)	[(8,1,1),(3...	79.80	6053.40	75.85
634	(1,1,0,0)	(2,1,1,1)	[(6,3,1),(4...	80.42	6055.74	70.29
735	(1,1,0,0)	(1,2,3,3)	[(5,3,1),(3...	86.94	6005.19	70.20
705	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	86.94	6099.37	70.14
735	(1,1,0,0)	(2,2,3,3)	[(7,3,1),(4...	87.74	6090.38	67.43
756	(1,1,0,0)	(3,2,3,3)	[(7,3,1),(4...	87.74	6076.67	67.29
734	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	87.92	6075.50	67.15
778	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	88.01	6078.30	68.14
720	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	88.23	6084.50	68.05
701	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	88.27	6039.36	67.56
780	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	88.48	6040.63	67.43
733	(1,1,0,0)	(2,2,3,3)	[(7,3,1),(4...	97.74	6590.38	67.43
754	(1,1,0,0)	(3,2,3,3)	[(7,3,1),(4...	97.74	6576.67	67.29
734	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	97.92	6575.50	67.15
770	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	98.01	6678.30	68.14
722	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	98.23	6684.50	68.05
714	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	98.27	6639.36	67.56
716	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	98.48	6640.63	67.43
736	(1,1,0,0)	(3,2,3,3)	[(7,3,1),(4...	100.22	6640.74	66.26
744	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	103.39	6740.74	65.20
605	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	103.51	6740.50	65.12
667	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	104.09	6743.23	64.78

Figure 36. The dialogue menu of the evolutionary process



Line 41 assembly LAYOUT1: Probable error in function evaluation.

Tool No 1234567890 Total Cavity Number 4 Total No. of Ref. Models 4

Item	Comp_id	Ref_Name	X	Y	Z	Angle
1	001	part1	0.00	100.00	0.00	0.00
2	002	part2	100.00	50.00	0.00	0.00
3	003	part3	100.00	50.00	0.00	0.00
4	005	part4	0.00	100.00	0.00	0.00

Current Generation: 377

Average CP = 104.62 Average C = 6742.76 Average P = 64.45

Best CP = 74.02 Best C = 6000.56 Best P = 81.07

Individual	Chromosome(s1)	Chromosome(s2)	Chromosome(s3)	C-P	Cost	Performance
677	(0,1,0,0)	(1,2,3,3)	[(6,1,1),(4...	74.02	6000.56	81.07
767	(1,1,0,0)	(1,2,3,3)	[(6,1,1),(4...	79.80	6053.40	75.85
731	(1,1,0,0)	(1,2,3,3)	[(8,1,1),(3...	79.80	6053.40	75.85
634	(1,1,0,0)	(2,1,1,1)	[(6,3,1),(4...	80.42	6055.74	70.29
735	(1,1,0,0)	(1,2,3,3)	[(6,1,1),(4...	84.11	6380.38	75.85
705	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	86.94	6099.37	70.14
735	(1,1,0,0)	(2,2,3,3)	[(7,3,1),(4...	87.74	6090.38	67.43
756	(1,1,0,0)	(3,2,3,3)	[(7,3,1),(4...	87.74	6076.67	67.29
734	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	87.92	6075.50	67.15
778	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	88.01	6078.30	68.14
720	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	88.23	6084.50	68.05
701	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	88.27	6039.36	67.56
780	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	88.48	6040.63	67.43
733	(1,0,0,0)	(2,1,1,1)	[(5,3,1),(7...	94.33	6631.04	70.29
754	(1,1,0,0)	(3,2,3,3)	[(7,3,1),(4...	97.74	6576.67	67.29
734	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	97.92	6575.50	67.15
770	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	98.01	6678.30	68.14
722	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	98.23	6684.50	68.05
714	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	98.27	6639.36	67.56
716	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	98.48	6640.63	67.43
736	(1,1,0,0)	(1,2,3,4)	[(5,3,1),(2...	100.45	6130.59	61.03
744	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	103.39	6740.74	65.20
605	(1,1,0,0)	(2,1,3,3)	[(7,3,1),(4...	103.51	6740.50	65.12
667	(1,1,0,0)	(1,2,3,3)	[(7,3,1),(4...	104.09	6743.23	64.78

Figure 37. The graphical user interface of the evolutionary process

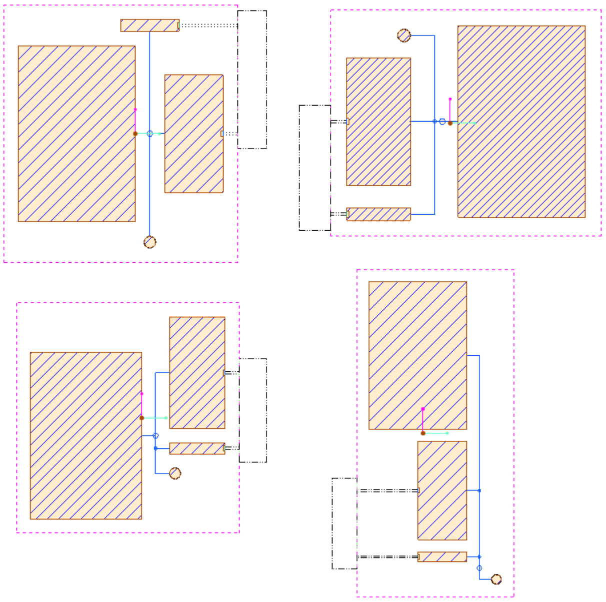
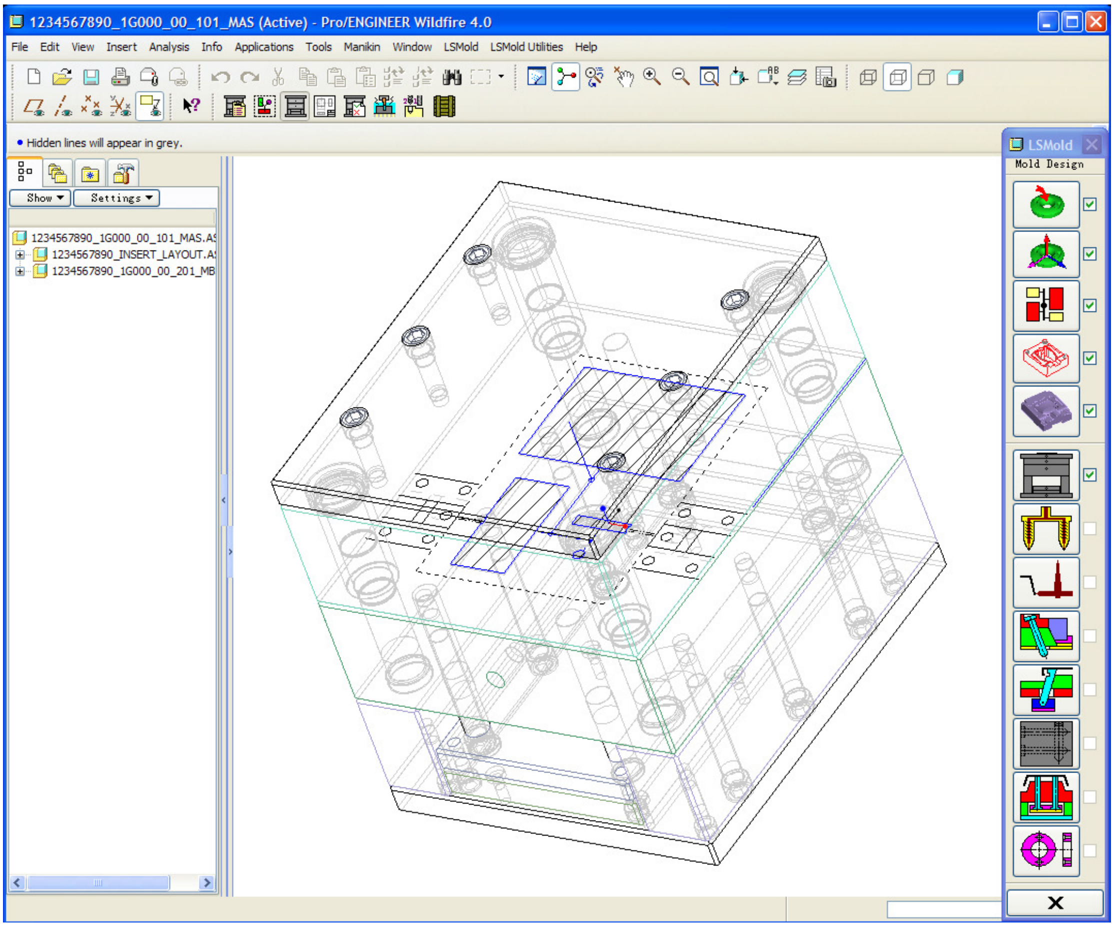


Figure 38. Some examples of FMCRLD evolved by the prototype system

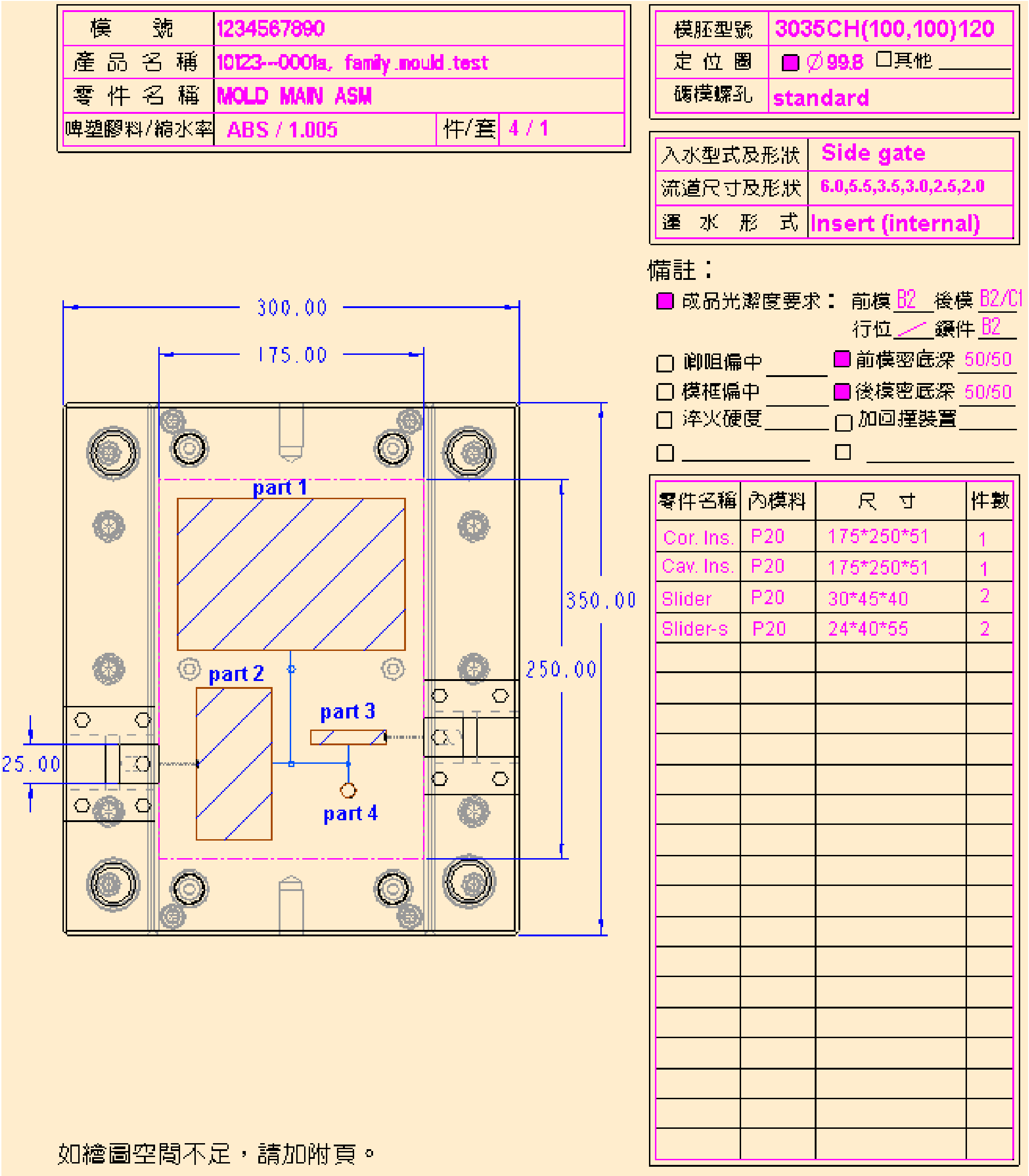


1234567890_1G000_00_101_MAS (Active) - Pro/ENGINEER Wildfire 4.0

• Hidden lines will appear in grey.

1234567890_1G000_00_101_MAS.AS
1234567890_INSERT_LAYOUT.AS
1234567890_1G000_00_201_MB

Figure 39. The 3D mould layout design model of this experimental case study



模 號	1234567890		
產 品 名 稱	10123--0001a, family.mould.test		
零 件 名 稱	MOLD MAIN ASM		
啤塑膠料/縮水率	ABS / 1.005	件/套	4 / 1

模胚型號	3035CH(100,100)120
定 位 圈	■ ∅99.8 □其他 ______
碼模螺孔	standard

入水型式及形狀	Side gate
流道尺寸及形狀	6.0,5.5,3.5,3.0,2.5,2.0
運 水 形 式	Insert (internal)

備註：

■ 成品光潔度要求： 前模 B2 後模 B2/C1

行位 ⟋ 鑲件 B2

□ 唧咀偏中 ______ ■ 前模密底深 50/50

□ 模框偏中 ______ ■ 後模密底深 50/50

□ 淬火硬度 ______ □ 加回撞裝置 ______

□ ______________ □ ______________

零件名稱	內模料	尺 寸	件數
Cor. Ins.	P20	175*250*51	1
Cav. Ins.	P20	175*250*51	1
Slider	P20	30*45*40	2
Slider-s	P20	24*40*55	2

如繪圖空間不足，請加附頁。

Figure 40. The mould layout drawing generated by the ICMLDS prototype in this experimental case study

In this experiment, three mould design engineers (Designers A,[*] B[†] and C[‡]) were invited to design the same family mould using their traditional manual design method.[§] The design lead time was recorded and the cost performance values of their designs were calculated based on the same evaluation method proposed in this research. The results were used to compare the design quality and efficiency of the ICMLDS prototype with existing manual design methods. The detailed FMCRLD drawings created by Designers A, B and C, and the ICMLDS prototype can be found in Appendix F.4.

---

[*] *Mr. Chen Guang Yu is a junior mould design engineer in Luen Shing Tools Limited. He has about one year of experience doing FMCRLD.*

[†] *Mr. Chen Lian Gji is a junior mould design engineer in Luen Shing Tools Limited. He has about one year of experience doing FMCRLD.*

[‡] *Mr. Zhang Jian is a senior mould design engineer in Luen Shing Tools Limited. He has over ten years of experience doing FMCRLD.*

[§] A d*etailed description of existing manual design methods for FMCRLD used in Luen Shing Tools Limited can be found in Section 1.4.2 of the portfolio submission 1- Research Project proposal.*

5.2 Verification and analysis of results[*]

An experienced senior mould flow CAE engineer[†] was invited to verify the mould filling performance of different FMCRLD alternatives generated from the ICMLDS prototype. Other performance values (P_c and P_d) and the estimated cost values (C_m, C_n, C_s, C_r, C_j and C_m) of different FMCRLD alternatives were verified and compared by experienced senior mould design engineers[‡] based on their experience and expertise in the area of family mould design.

Due to the complexity of FMCRLD optimisation, it is impossible to prove that the best FMCRLD obtained from the ICMLDS prototype is a true global optimum solution. For testing the prototype, the program was run 5 times repeatedly using a larger population size (800) and longer stall generation (300). The result showed that the same best FMCRLD solution was obtained. This demonstrated the repeatability in performance of GA as the difference in optimal result for different

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[*] *A more detailed description and discussion of verification and analysis of results can be found in Section 3.2 and Chapter 4 of the 4th portfolio submission – ICMLDS implementation and verification.*

[†] *Mrs Zeng Li Juan was invited to perform mould filling analysis and artificial filling balance using the MOLDFLOW® Plastics Insight software package and verify the mould filling performance of the system outputs based on her experience. Mrs Zeng Li Juan has been working for Luen Shing Tools Limited as a senior mould flow CAE engineer for over six years.*

[‡] *Mr Ho Tak Piu and Mr Choi Sau Yun were invited to verify and compare the FMCRLD generated from the ICMLDS prototype. Both of them have been working for Luen Shing Tools Limited as senior mould design engineers for over ten years.*

runs was insignificant. This also proved that this best FMCRLD solution was not a local optimal solution in this case study. As shown in Figure 41, the best result of the 5 runs obtained from the ICMLDS prototype is illustrated with the graph of Average CP and Best CP Vs. generations. The six different FMCRLD alternatives (starting from *a* to *f*) attached to the Best CP curve represent the best individual obtained in the population in different generations. Their chromosomes and the weighted CP values are listed in Table 3. The result demonstrated that better offspring could be reproduced from parents through the innovative crossover and mutation operations without producing invalid offspring. Using the steady-state population model, the best individuals from a given generation can always be preserved in the next generation. The worst individual is replaced by the better offspring in each generation which drives the whole population to improve from generation to generation with high selection pressure. Because of the higher weights on P_f, P_r, C_m and C_n, individuals with more balanced runner layout system, smaller mould base and mould insert have better fitness values to survive and more chances to pass on their successful traits. All individuals violating the mould base size constraint are penalized and replaced eventually. At 87 generations, Design (e) appeared and kept the top position for a number of generations. Then a new Design (f) was introduced into the population from mutation on Design (e) at 177 generations.

Finally, the algorithm started to converge and stopped at 377 generations automatically because there was no change in the best CP value for over 200 generations. The running time was 78 seconds. The statistics of this experimental case study showed that the average CP value of the population was improved from 182.46 to 102.62 (see the "Average CP" curve in Figure 41). The best CP value was improved from 123.54 to 74.02 (see the "Best CP" curve in Figure 41). The best values of Cost (C) and Performance (P) achieved by Design (f) were 6000.56 and 81.07 respectively (see Table 3).

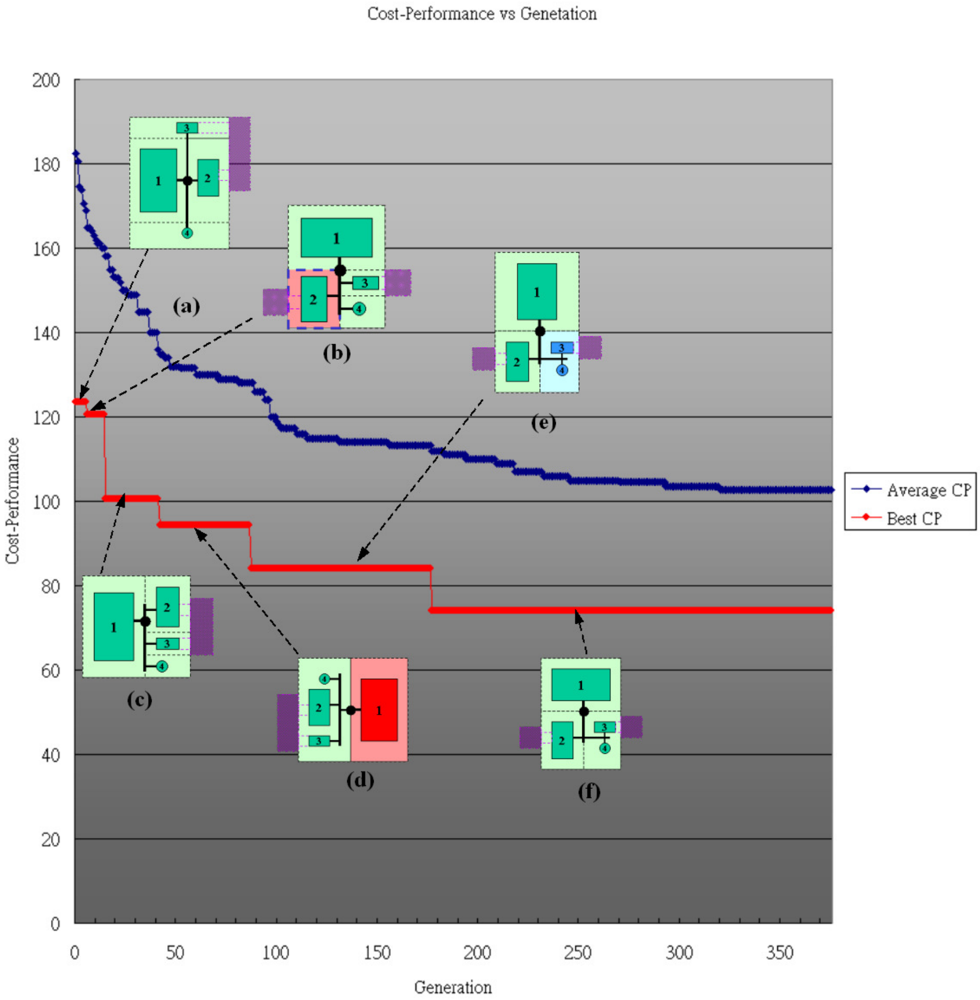
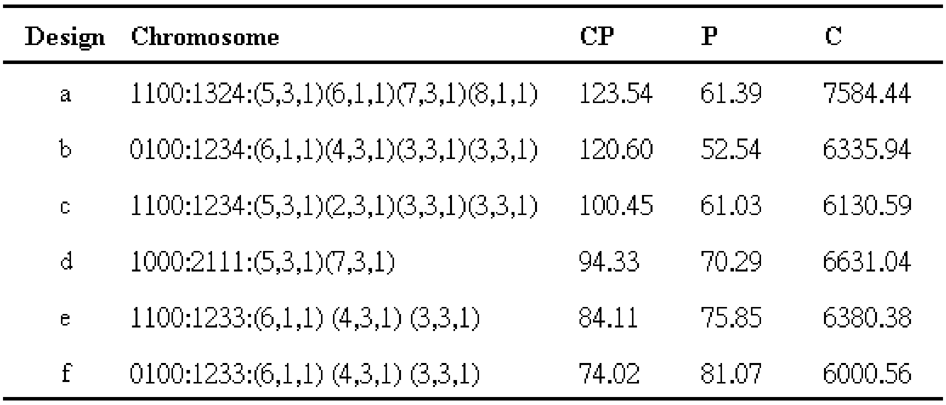


Figure 41. The graph of Average CP and Best CP Vs. generation



Design	Chromosome	CP	P	C
a	1100:1324:(5,3,1)(6,1,1)(7,3,1)(8,1,1)	123.54	61.39	7584.44
b	0100:1234:(6,1,1)(4,3,1)(3,3,1)(3,3,1)	120.60	52.54	6335.94
c	1100:1234:(5,3,1)(2,3,1)(3,3,1)(3,3,1)	100.45	61.03	6130.59
d	1000:2111:(5,3,1)(7,3,1)	94.33	70.29	6631.04
e	1100:1233:(6,1,1) (4,3,1) (3,3,1)	84.11	75.85	6380.38
f	0100:1233:(6,1,1) (4,3,1) (3,3,1)	74.02	81.07	6000.56

Table 3. The weighted cost performance values and the chromosomes of each outstanding individual at different generations

In this research, the P_f and P_r values in relation to the filling balance performance were verified by the experienced mould flow CAE engineer based on the filling analysis results using the MOLDFLOW® Plastics Insight software package. In practice, the artificial filling balance is performed by manually adjusting the diameters of each individual runner segment and running filling analysis iteratively based on a mould flow CAE engineer's experience. The filling analysis results of Designs (d) and (f) after artificial filling balance are shown in Figures 42 and 43 respectively. According to the mould flow CAE engineer's suggestion, the diameters of runner segments (R1, R2, R3, R4, R5 and R6) of Design (d) needed to be adjusted so as to achieve an acceptable filling balance (see dimensions in brackets in Figure 42). It was noticed that the diameter of runner R5 was smaller than the recommended runner diameter (approximately 1.5 times the normal wall thickness 1.5 mm of Part 2) for sufficient filling and packing of Part 2. Besides, the significant variation of runner diameters (such as R5 to R3 and R2 to R1) might cause possible flow hesitation such that the artificial filling balance achieved based on Design (d) was sensitive to any slight variation in injection moulding process and moulding property of plastic, leading to a narrow process window. If a family mould is actually manufactured based on bad FMCRLD (such as Design (d) in this case), it will require a large amount of money and time to rework the entire mould because the filling imbalance problem cannot be simply resolved by enlarging the runner diameters. On the other hand, only three runner segments (R2 R3, R5) of Design (f) needed to be further adjusted for artificial filling balance. The result showed that an acceptable filling balance could be achieved and all runner diameters could meet the requirements of recommended runner diameters for effective filling and packing of the moulding parts and standard milling cutter diameters for easy manufacturing. Besides, no significant variation of runner diameters at branching node could be found in Design (f). Hence, the artificial filling balance based on Design (f) could be achieved with a wider process window compared with Design (d). These mould flow filling analysis results verified that Design (f) having a higher P_f (90.91) and P_r (98.36) can achieve a better filling balance performance over Design (d) having a lower P_f (84.03) and P_r (75.00). In other words, the simple P_f and P_r values have proven to be efficient to quantify the comparison of filling balance performance among different FMCRLD for numerous fitness evaluations in the GA.

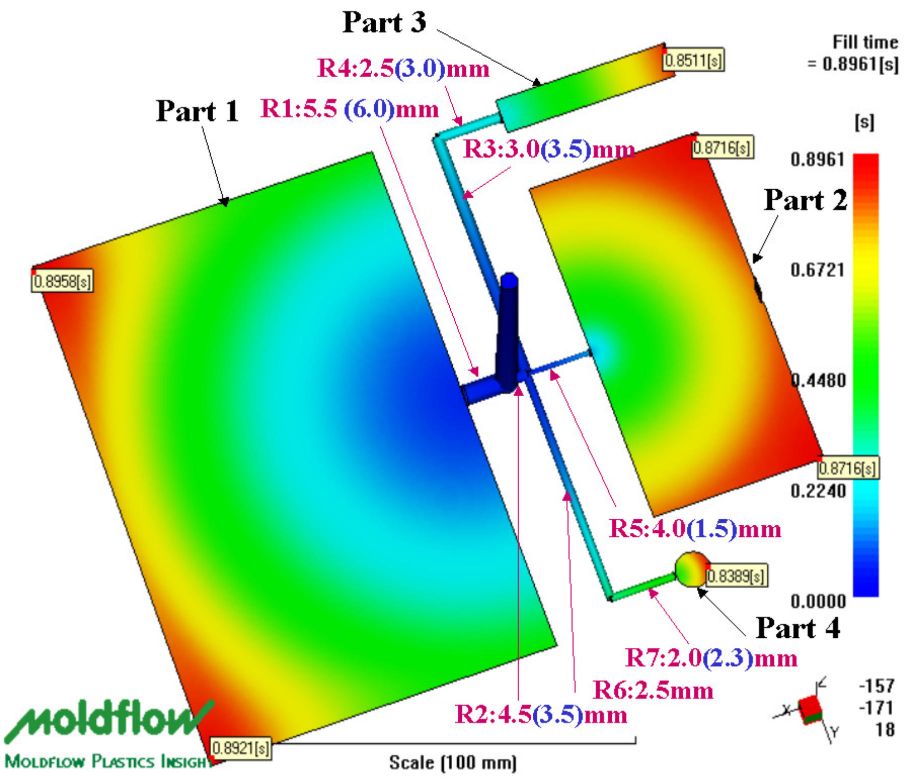


Figure 42. The filling analysis result of Design (d) after artificial filling balance

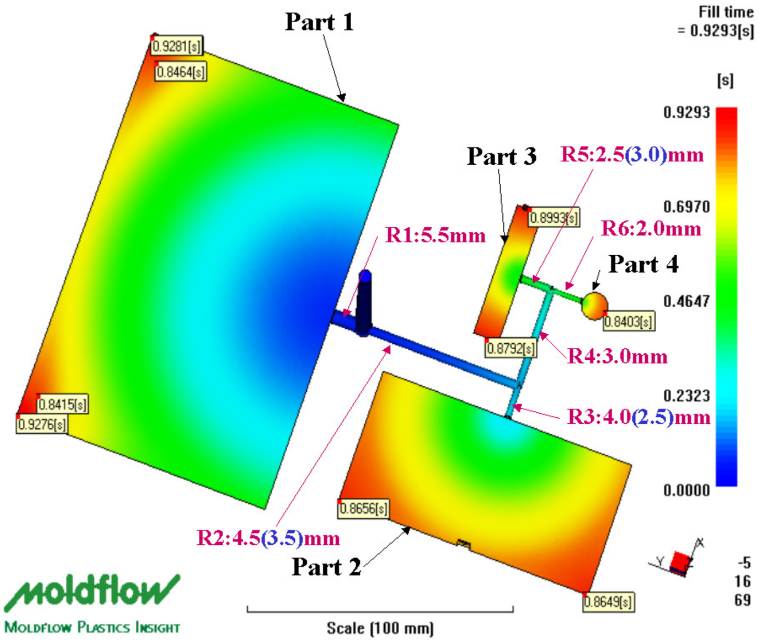
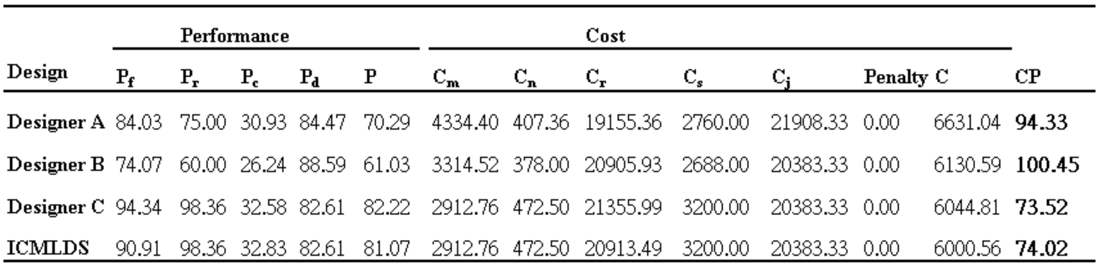


Figure 43. The filling analysis result of Design (f) after artificial filling balance

The detailed cost and performance values of different FMCRLD designed by different mould designers and the ICMLDS prototype are listed in Table 4. Based on the same weighting ratios of various performance factors and cost factors, the overall weighted Cost Performance (CP) values, Performance (P) values and Cost (C) values of their FMCRLDs were calculated. As shown in Figure 44, the result showed that the ICMLDS prototype could score a high CP (74.02) value, which can compete with the best CP (73.52) value achieved by Designer C in this case study. The FMCRLD generated by the prototype system can improve the CP value by 26.3% compared with the worst FMCRLD done by less experienced Designer A.



Design	Performance					Cost							
	P_f	P_r	P_c	P_d	P	C_m	C_n	C_r	C_s	C_j	Penalty	C	CP
Designer A	84.03	75.00	30.93	84.47	70.29	4334.40	407.36	19155.36	2760.00	21908.33	0.00	6631.04	**94.33**
Designer B	74.07	60.00	26.24	88.59	61.03	3314.52	378.00	20905.93	2688.00	20383.33	0.00	6130.59	**100.45**
Designer C	94.34	98.36	32.58	82.61	82.22	2912.76	472.50	21355.99	3200.00	20383.33	0.00	6044.81	**73.52**
ICMLDS	90.91	98.36	32.83	82.61	81.07	2912.76	472.50	20913.49	3200.00	20383.33	0.00	6000.56	**74.02**

Table 4. The detailed cost and performance values of different FMCRLD alternatives designed by different mould designers and the ICMLDS prototype

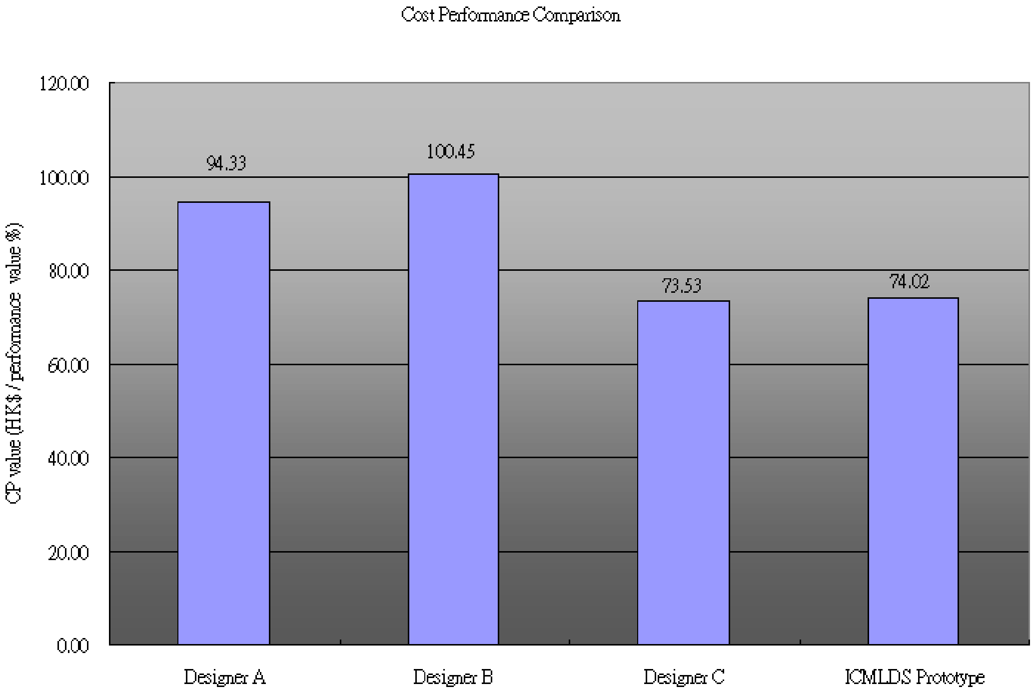


Figure 44. The Cost Performance (CP) comparison among different FMCRLD alternatives designed by different mould designers and the ICMDLS prototype

With regard to the design lead time comparison (see Figure 45), the less experienced mould designers (Designers A and B) needed more than 50 minutes to think of the conceptual layout design and spent another 60 minutes on creating the detail CAD drawing. For the experienced mould designer (Designer C), it still took 25 minutes to finish the conceptual layout design and 40 minutes to finish the detail CAD drawing. In this case study, the prototype system required about 5 minutes for the data input process and 6.5 minutes for the computation process (5 runs). The detail CAD drawing was then automatically generated within one second. The comparison result showed that using the prototype system to perform FMCRLD can dramatically reduce the design lead time by over 94% compared to less experienced mould designers (Designers A and B) and over 90% compared to the most experienced one (Designer C).

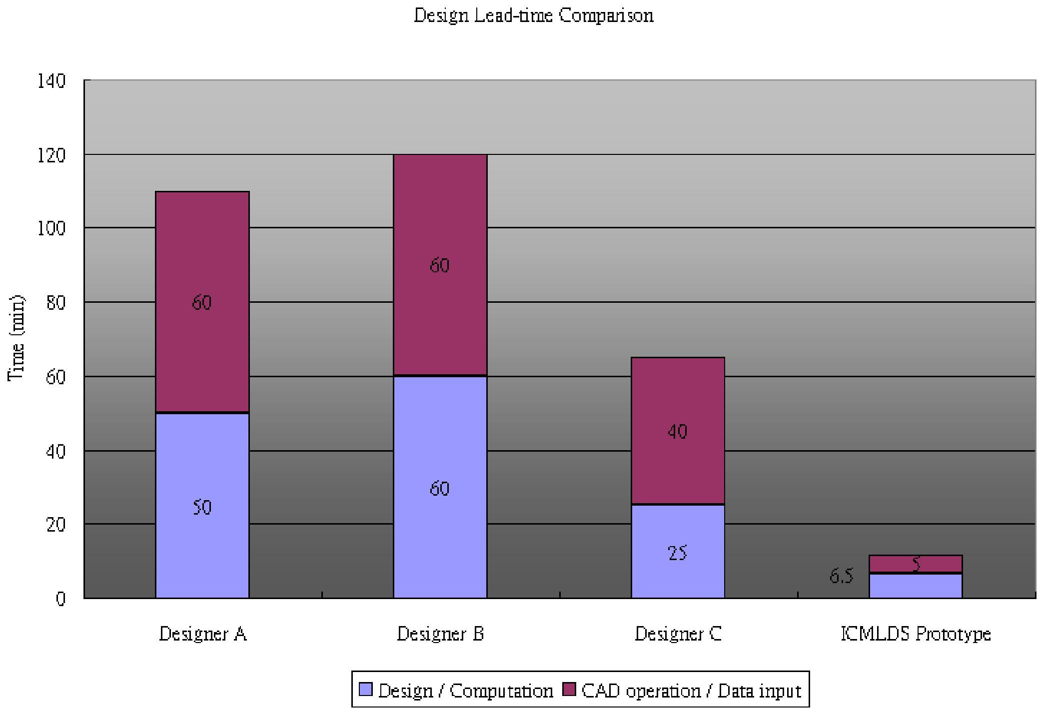


Figure 45. The design lead time comparison among different mould designers and the ICMLDS prototype

As discussed in Section 1.4, filling balance analysis of numerous different FMCRLD alternatives involves costly, tedious and time-consuming data preparation and computationally intensive processes. It is virtually impossible for mould designers to use existing commercial CAE software packages to search for the global optimum artificial filling balance solution. This case study showed that even an experienced mould flow CAE engineer could not achieve the global optimum artificial filling balance solution unless a good FMCRLD is provided. Taking this case study as an example, it took about 7 hours to perform artificial filling balance on 4 FMCRLD alternatives in order to achieve the best solution while the ICMLDS prototype could already provide the best FMCRLD for mould flow CAE engineers to perform artificial filling balance at the beginning. As shown in Figure 46, the ICMLDS prototype can save a lot of time on performing costly and time-consuming artificial filling balance on numerous different FMCRLD alternatives.

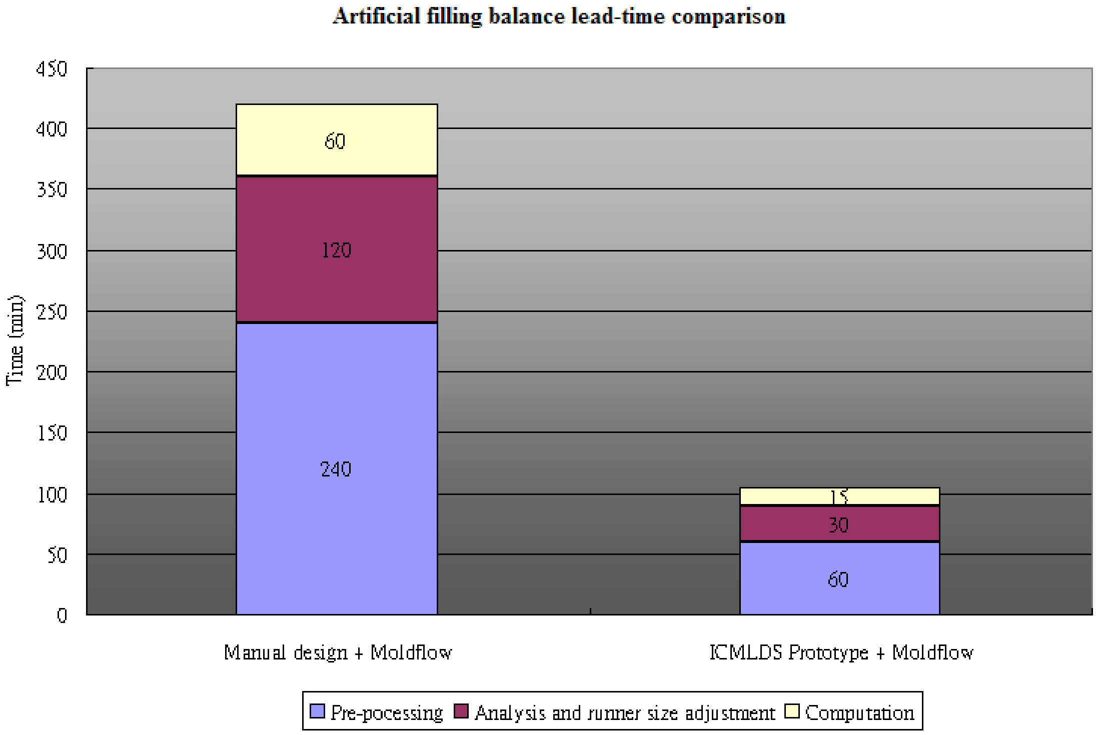


Figure 46. Artificial filling balance lead time comparison between manual design and the ICMLDS prototype

5.3 Implementation examples

In this research, two production family moulds of a real-life toy product were chosen as implementation examples to demonstrate how the ICMLDS prototype can accelerate mould designers' design alternative exploration, exploitation and optimisation for better design in less time.

5.3.1 Case study I

In this case study, the junior mould designer (Designer A) was invited to design a family mould of seven dissimilar parts moulded in ABS (Polylac PA-757) using the ICMLDS prototype. The detailed drawings of Parts A-G are shown in Figure G.1.1-G.1.6 in Appendix G.1. The specification of the parts is summarised in Table G.2.1 in Appendix G.2. The weighting ratios of the five cost factors need to be reallocated because there is no slider in this family mould (see Table G.3.1 in Appendix G.3). Similar to the experimental case study (see Section 5.1), the program was run 5 times repeatedly with the same setting of GA parameters first. If necessary, the GA parameters were adjusted according to the optimisation result. It took about 15 minutes to complete the 5 runs. The best solution of the 5 runs is shown in Figure 47. Based on this FMCRLD solution, Designer A attempted to achieve a higher P_f and P_r values without increasing the existing C_n and C_m values by slightly adjusting the cavity positions of Parts C, E, F and G as shown in Figure 48. Then the ICMLDS prototype updated the FMCRLD and recalculated all the performance and cost factors automatically. It provided a rapid design visualisation and design feedback for Designer A to fine-tune the design. As shown in Table 5, although the C_r value was increased from 20004.20 to 20569.96, the P_f value was increased from 80.60 to 86.20. The CP value was further improved from 100.61 to 99.47. Subsequently, the ICMLDS prototype automatically generated the mould assembly model and the associated mould drawing (see Figure G.4.1 in Appendix G.4) within the commercial MCAD system for downstream design and manufacturing processes, streamlining the whole mould development workflow. After the senior mould designer (Designer C) approved this mould design, the mould was made accordingly. The mould flow filling analysis results of layout 1 and layout 2 can be found in Appendix G.5. During the first shot testing, it was observed that this family mould could produce the moulding parts without any major moulding defect, such as fill imbalance (see Figure 49). The result proved that this FMCRLD could achieve a good filling balance performance with minimum costs of runner, mould base, mould insert and injection moulding.

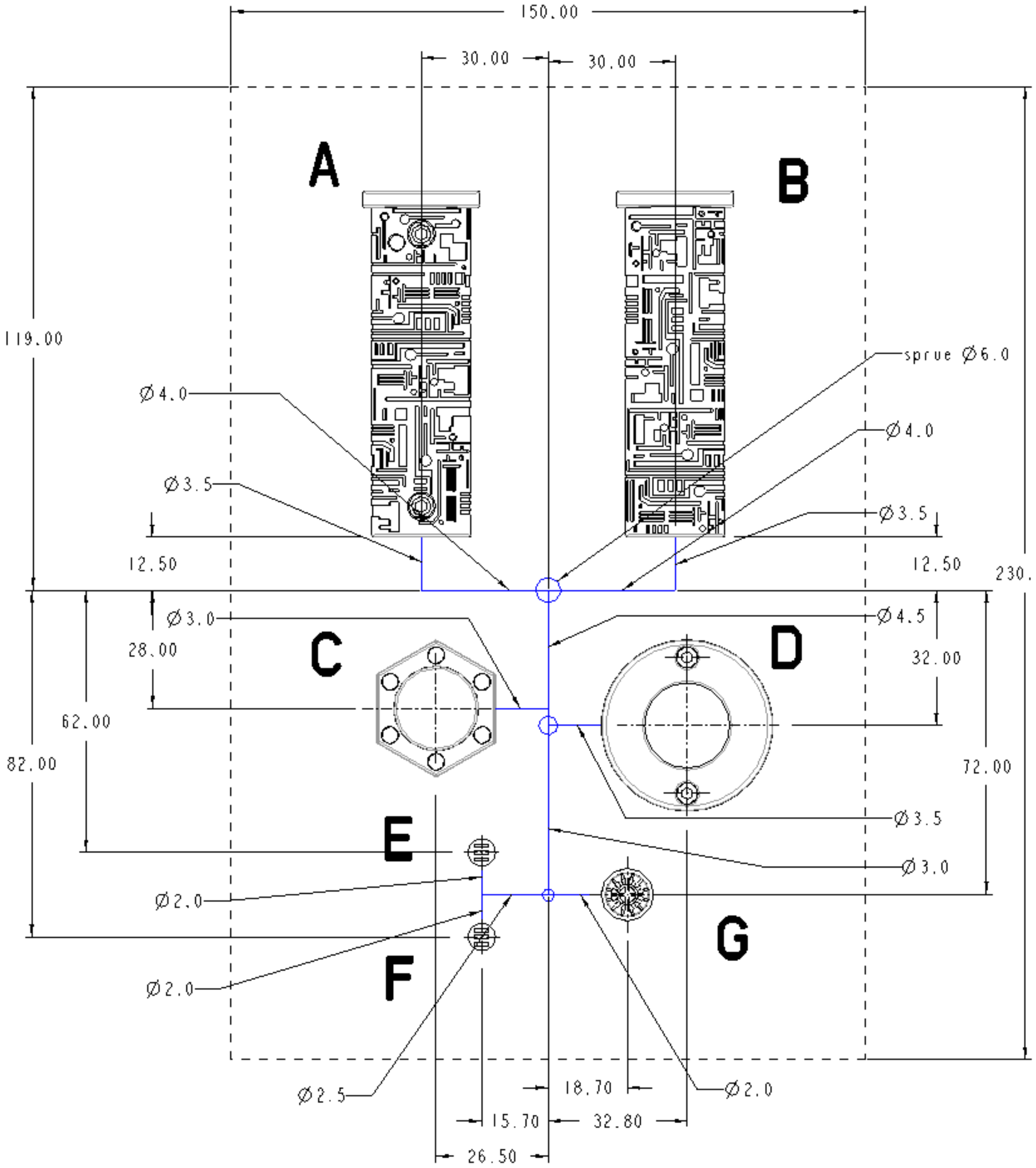


Figure 47. The best FMCRLD (layout 1) solution generated by the ICMLDS prototype

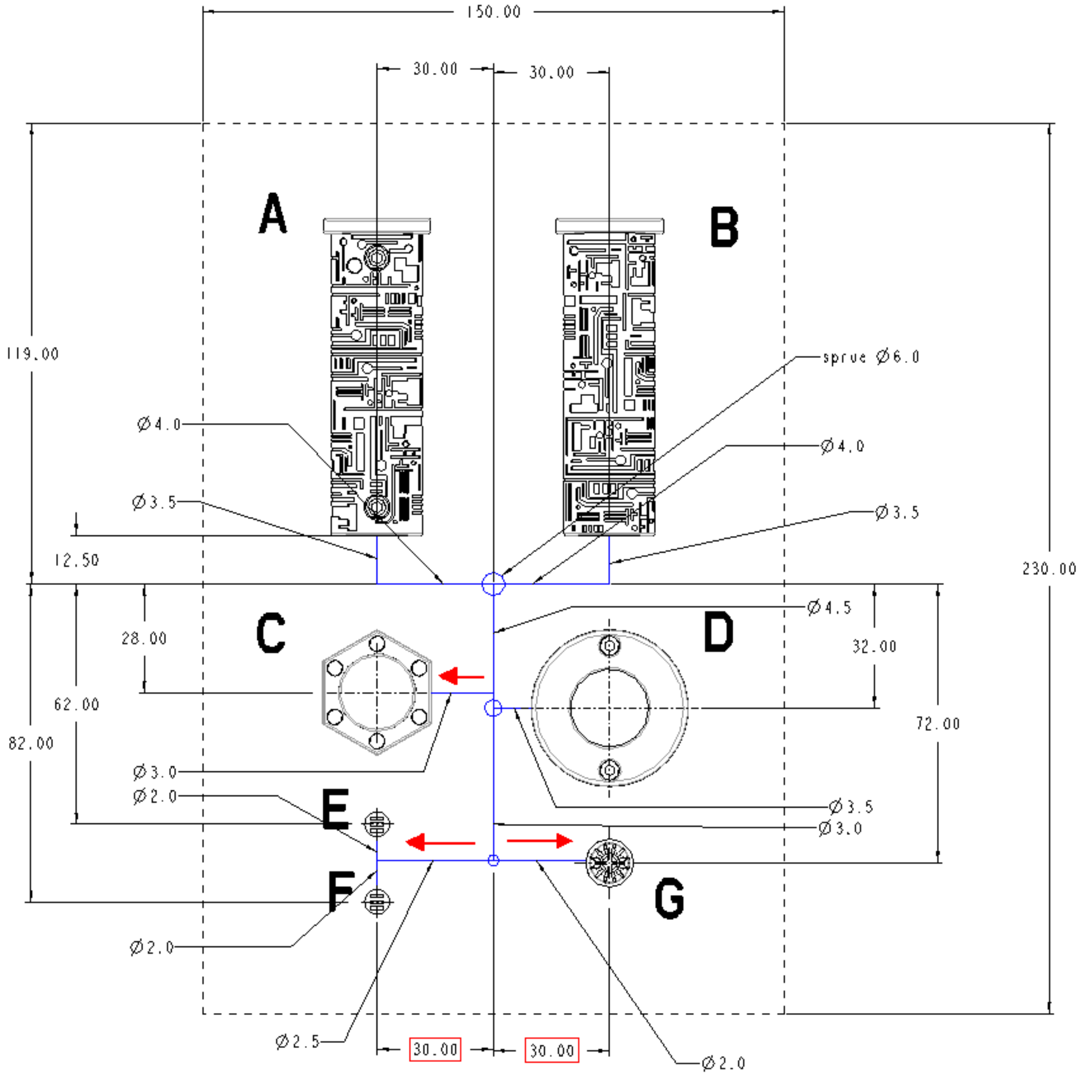


Figure 48. The final FMCRLD (layout 2) modified by mould designer A

	P_f	P_r	P_c	P_d	P	C_n	C_m	C_r	C_j	C	CP
weight	0.35	0.35	0.2	0.1		0.2	0.5	0.2	0.1		
layout 1	80.60	90.00	19.20	87.00	72.25	372.60	2310.12	20004.20	20383.30	7268.75	100.61
layout 2	86.20	90.00	19.20	87.00	74.21	372.60	2310.12	20569.96	20383.30	7381.90	**99.47**

Table 5. The cost performance values of layouts 1 and 2 in case study I

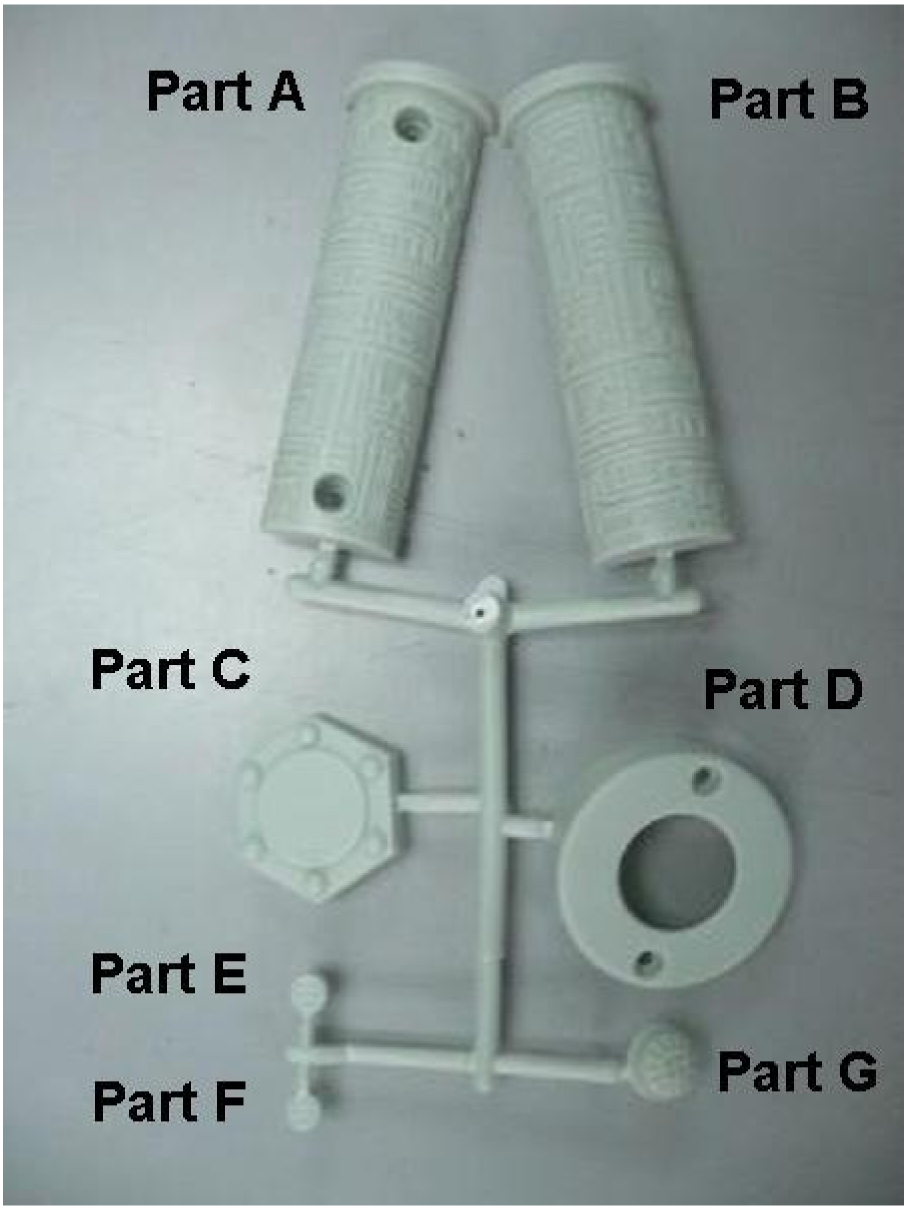


Figure 49. The photo of the final test shot of the family mould implemented in case study I (*Courtesy: the supporting company*)

5.3.2 Case study II

In this case study, another junior mould designer (Designer B) was asked to design a family mould of seven dissimilar parts moulded in non-toxic PVC using the ICMLDS prototype. The detailed drawings of Parts A-G are shown in Figures H.1.1-H.1.7 in Appendix H.1. The specification of the parts is summarised in Table H.2.1 in Appendix H.2. Unlike the previous two case studies, mould inserts of this family were made of beryllium-copper alloy casting. In practice, a set of mould cavity and core inserts for each part is made individually. This means that this family mould has 7 individual sets of mould inserts instead of one single set of mould inserts. Therefore, the minimum offset distance between cavities was adjusted from the default of 12 mm to 25 mm. Besides, the weighting ratios of the five cost factors need to be reallocated because the cost of the slider can be omitted and the material cost of beryllium-copper alloy is expensive[*] in this case study (see Table H.3.1 in Appendix H.3). Similar to the experimental case study (see Section 5.1), the program was run 5 times repeatedly. It took about 23 minutes[†] to complete the 5

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[*] *According to the costing data provided by the purchasing department of the supporting company, the average material cost of beryllium-copper alloy is HK$220 /kg while that of ordinary mould steel is HK$27 /kg.*

[†] *Although both case studies I and II involved 7 dissimilar parts, the number of possible FMCRLD combinations in case study II was larger than in case study I because parts D and E of case study II involved two possible gate locations. It may be the possible reason why it took longer for the program to converge to an optimum solution in case study II.*

runs. Three outstanding FMCRLD solutions generated by the program were highlighted in this case study (see Figures 50-52). As shown in Table 6, layout 2 (see Figure 51) achieved a better overall P value (83.65) than the P value (76.66) scored by Layout 1 (see Figure 50) and the lowest C_r value (19668.21) among these three layouts, but at the expense of higher C_n and C_m values (3218.6 and 2310.12 respectively). Due to the heavy weight of C_n, the overall CP value of layout 1 (39.52) was lower than that of layout 2 (41.52). On the other hand, layout 3 (see Figure 52) was the best solution in this case study because of its excellent score in P_f (96.15). Based on this result, Designer B selected layout 3 and used the ICMLDS prototype to generate the mould assembly model and the associated mould drawing (see Figure H.4.1 in Appendix H.4). The mould was made accordingly after having been approved by the senior mould designer (Designer C). The first test shot of this family mould showed that all parts could be filled properly (see Figure 53). The successful result of this real case study showed that the ICMLDS prototype can assist less experienced mould designers in not only generating a number of good solutions automatically but also selecting the best trade-off solution between performance and cost considering a set of specific weights of criteria for different family moulds.

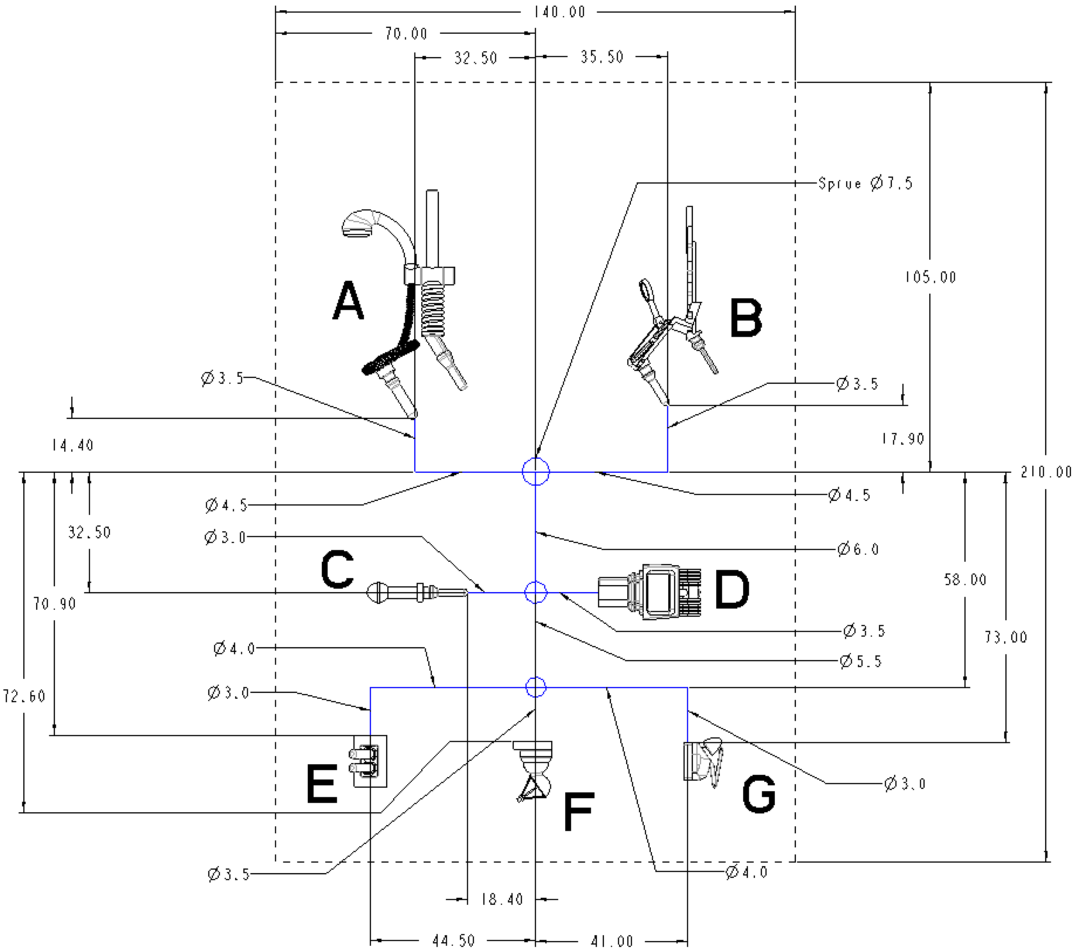


Figure 50. The outstanding FMCRLD (layout 1) solution generated by the ICMLDS prototype

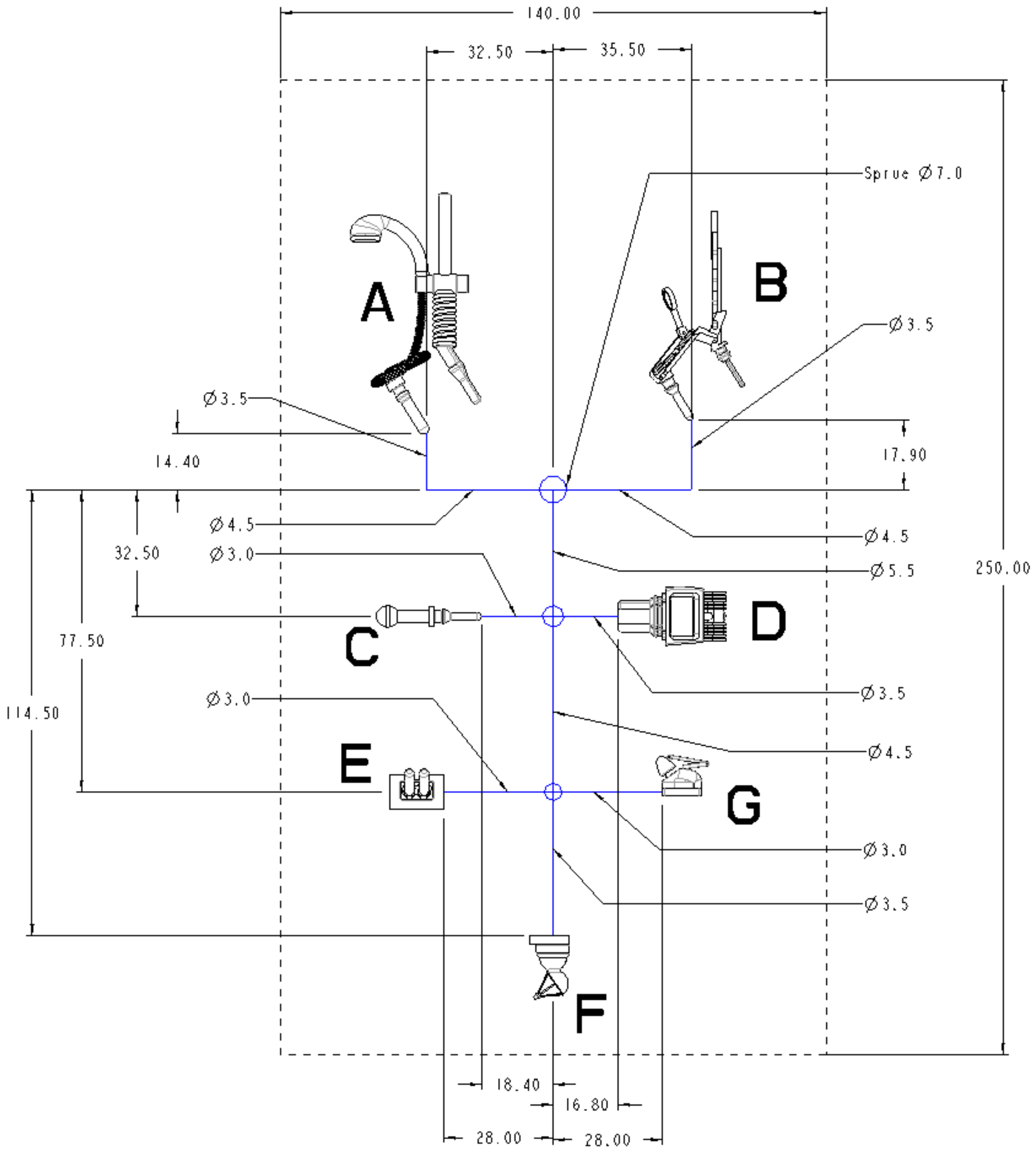


Figure 51. The outstanding FMCRLD (layout 2) solution generated by the ICMLDS prototype

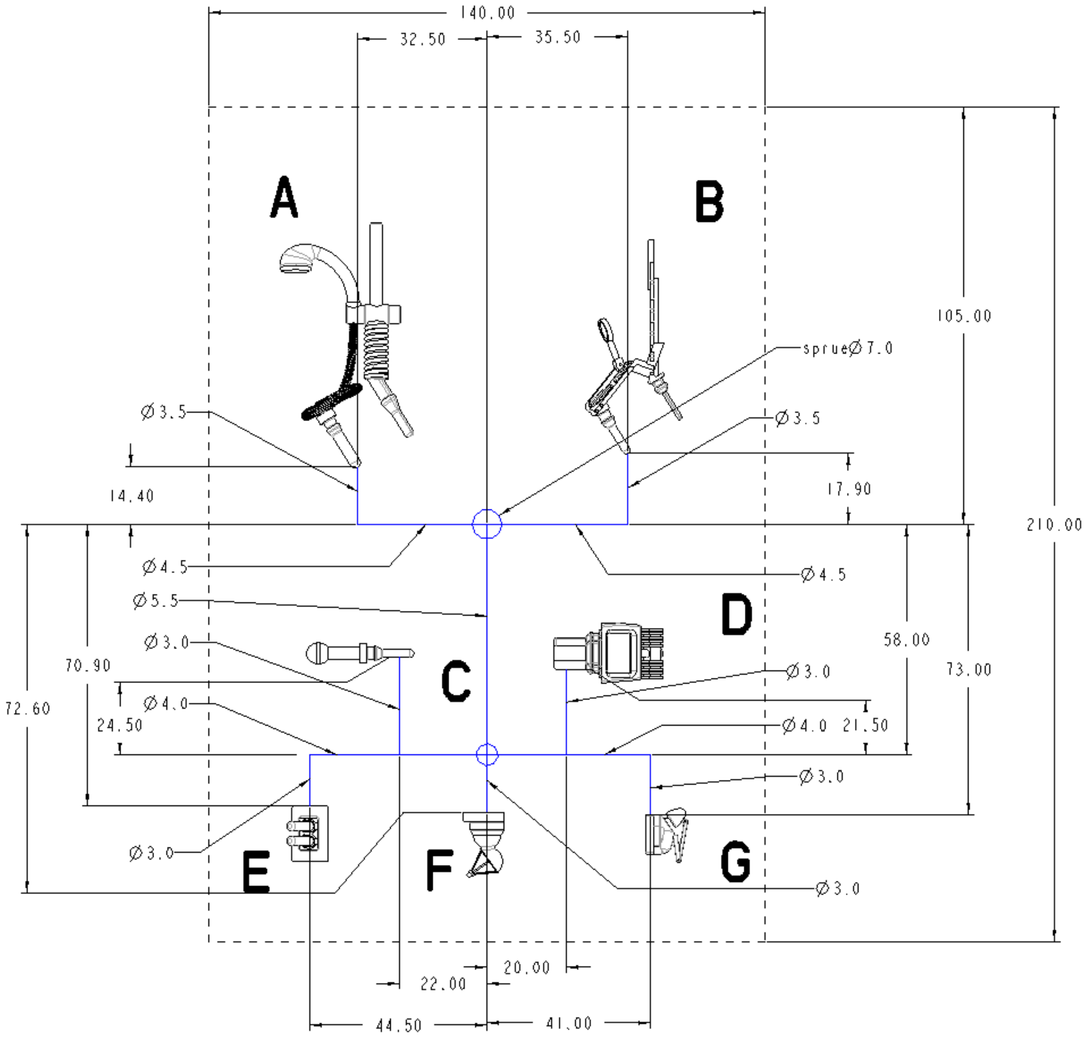


Figure 52. The outstanding FMCRLD (layout 3) solution generated by the ICMLDS prototype

	P_f	P_r	P_c	P_d	P	C_n	C_m	C_r	C_j	C	CP	Ranking
weight	0.35	0.35	0.2	0.1		0.89	0.09	0.01	0.01			
layout 1	81.30	65.60	78.60	95.20	76.66	2703.62	2127.96	22812.52	20383.30	3029.70	39.52	2
layout 2	79.50	80.00	95.60	87.00	83.65	3218.60	2310.12	19668.21	20383.30	3472.98	41.52	3
layout 3	96.15	80.00	78.60	95.20	86.89	2703.62	2127.96	21558.18	20383.30	3017.15	34.72	1

Table 6. The cost performance values of different FMCRLD alternatives with the modified setting of the weights of criteria used in case study II

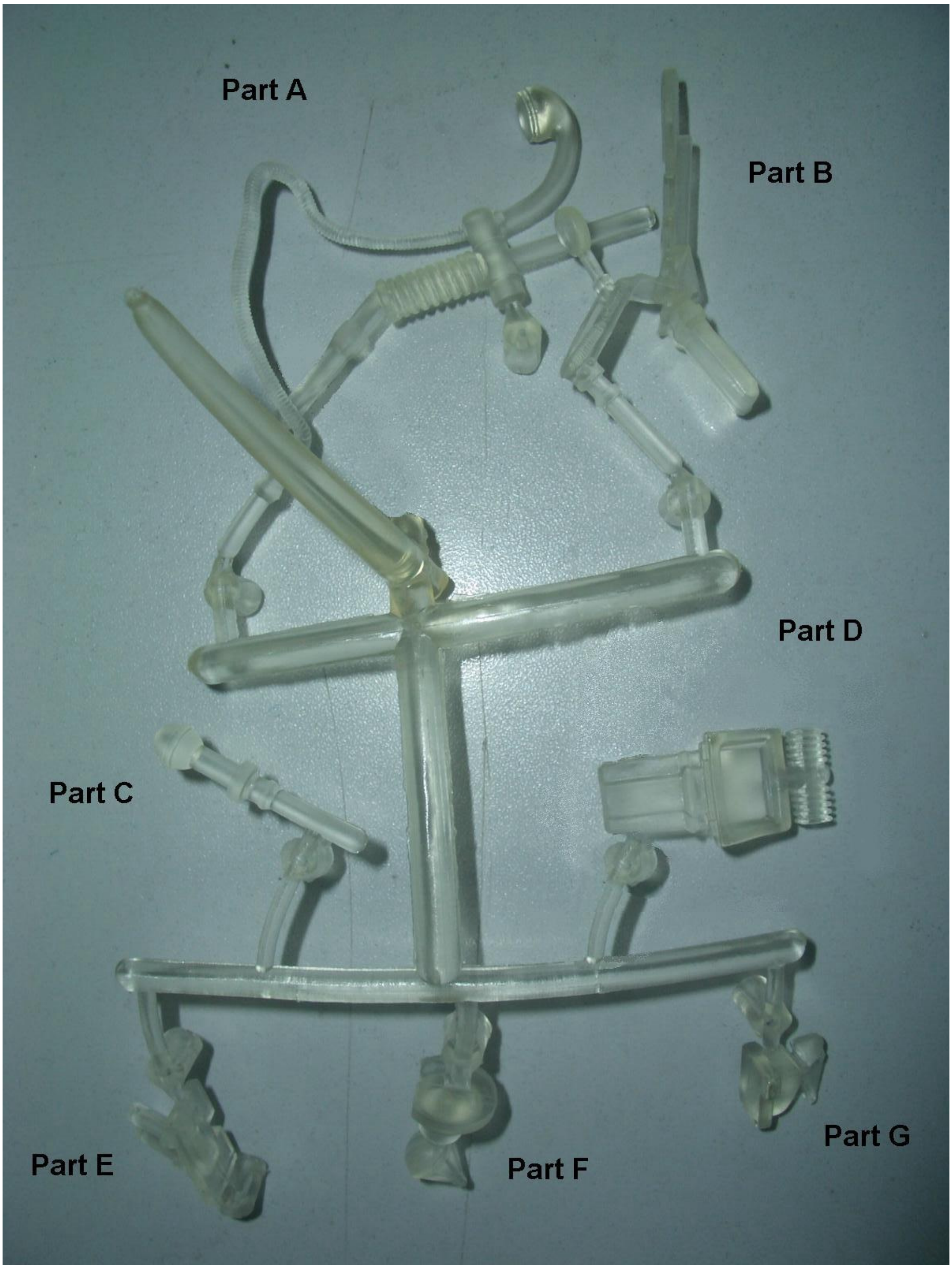


Figure 53. The photo of the final test shot of the family mould implemented in case study II (*Courtesy: the supporting company*)

5.4 Summary of results

In this research, an innovative evolutionary FMCRLD approach was successfully developed by solving the challenges in chromosome design, genetic operator design and fitness evaluation. The ICMLDS prototype seamlessly integrated with the advanced ProEngineer® CAD software package was implemented and verified in the supporting company. The implementation results show that the evolutionary FMCRLD using GA and SG is capable of automating FMCRLD and solving the complex combinatorial FMCRLD optimisation problems in practice. In the experimental case study, it was observed that mould designers often only try to find satisfactory solutions based on their experience and intuition rather than optimum ones because manual design exploration is tedious and time-consuming. However, the ICMLDS prototype can automatically explore the large feasible solution space and search for a global optimum FMCRLD solution, which can compete with the experienced mould designer's solution, and shorten the total design lead time dramatically (by over 90% compared to the experienced mould designer's design lead time in the experimental case study). In addition, the ICMLDS seamlessly embedded into the commercial MCAD system provided immediate workflow improvements over the traditional manual FMCRLD process with its ability to streamline the mould development workflow starting from the early CMLD phase to the later detail design phase and downstream manufacturing phase. Besides, it could save a huge amount of time and money spent on performing artificial filling balance on numerous different FMCRLD alternatives to achieve maximum filling balance performance with a wider process window. The results of the real case studies showed that the ICMLDS prototype could automatically generate multiple optimised solutions to a practical problem with specific family mould design objectives and constraints. With the aid of the ICMLDS prototype's instant visualisation and design feedback functions, mould designers can select the best trade-off solutions and manually modify the selected solution for further improvement if necessary. The successful first test shots of the family moulds implemented in the real case studies proved that the ICMLDS prototype can make less experienced mould designers capable of designing optimum FMCRLD solutions in the right direction at the beginning.

5.5 Limitations and further work

The limitations of this research can be categorised by three main issues: SG, fitness evaluation and GA optimisation issues. For the SG issues, the existing prototype cannot support multiple pin-point gates on the same moulding part and pin-point gate design because the majority of family moulds produced in the supporting company are single side gate. However, this limitation can be addressed in the future by adding a set of SG runner layout rules for supporting multiple pin-point gates on the same moulding part (see Figure 54) and runner layout design for pin-point gate (see Figure 55).

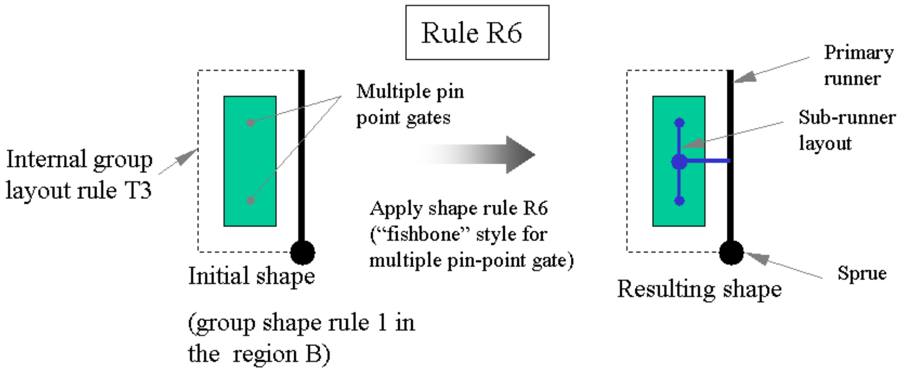


Figure 54. Example of an SG rule of cold runner layout design for multiple pin-point gates on a moulding part

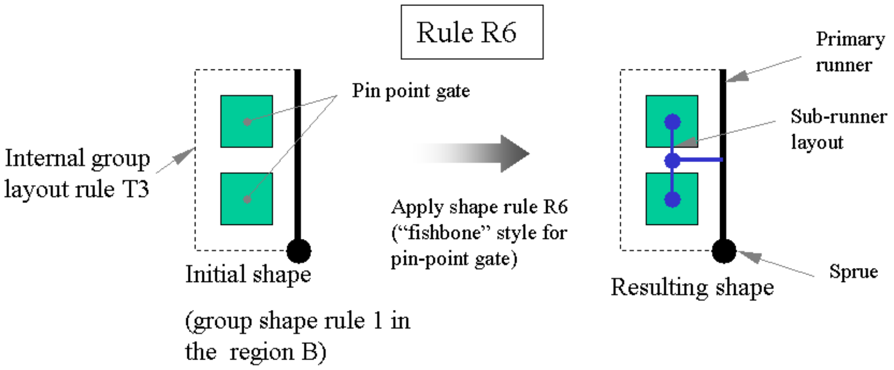
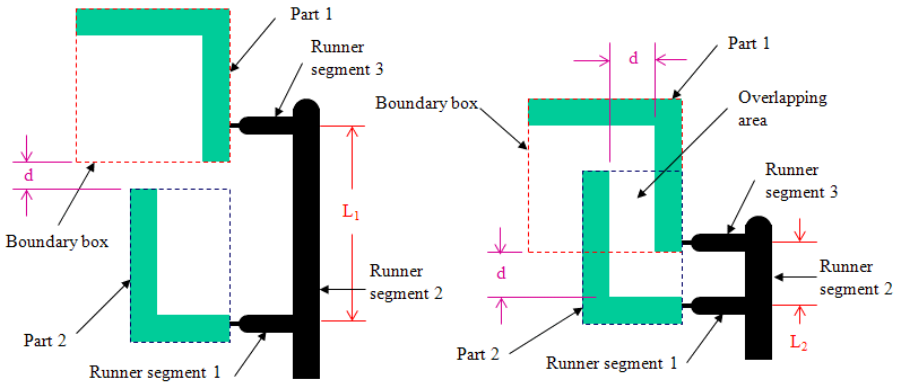


Figure 55. Example of an SG rule of cold runner layout design for pin-point gate on multiple moulding parts

With regard to the fitness evaluation issues, this research has two limitations. Firstly, the Cavity Flow Path (CFP) of a moulding part is approximately estimated and input into the program by mould designers according to its gating location, size and geometry at the beginning. The accuracy of the relative variation of CFP lengths of dissimilar moulded parts of a family mould influences the Flow Path Balance Performance (P_f) values of different FMCRLD alternatives in the population and therefore affects the optimisation result. Besides, different mould designers may give different CFP estimations for the same part which also affects the optimisation result. If necessary, the CFP of each dissimilar complex moulded part should be verified with the aid of a mould flow CAE software package beforehand. Further work on automatic estimation of CFP length of a moulding part is needed. Secondly, the simple weighted sum approach for combining a number of scoring components and penalty into a single fitness value may bury the significance of each individual criterion. In order to solve this problem, it is necessary to fine-tune the weights of the scoring components and the penalty for different sets of functional requirements of different types of family moulds (such as the ordinary family mould in case study I and the beryllium-copper alloy family mould in case study II). Further work is needed to establish a systematic method for determining these weightings. In the future, users can simply select different sets of standard and optimised weights of the scoring components and the penalty for different types of family mould and/or different customers.

For the GA optimisation issues, there are two limitations that need to be addressed in the future. Firstly, due to the limited time frame and the scope of this research, the ICMLDS prototype can only provide a general setting of GA parameters for mould designers to evolve FMCRLD, but it may not work for other cases. Mould designers may need to adjust the parameters and rerun the program repeatedly until satisfactory results are obtained. It is a well-known fact that a setting of GA parameters affects the efficiency and performance of the GA. However, it is a time-consuming process to search for the best combination of the GA parameters for each family mould. Over the decades, despite enormous research [175-181] on the setting of GA parameters, it still largely depends on experience or an ad hoc trial-and-error approach because the optimal setting is usually dependent upon the nature of the problem. In recent years, some innovative nature-inspired approaches for self-adaptive setting of GA parameters have been reported. For example, Ma [182] proposed a population dynamics theory for evolutionary computing that considers the population as a dynamic system over time (generations) and space (search space or fitness landscape) emulating the biological population dynamics in nature. Tahera et al. [183] proposed a GA with Gender-Age structure, Dynamic parameter tuning and Mandatory self-perfection scheme (GADYM) that combined the concept of gender and age in individuals and implemented the self-perfection scheme through sharing. This approach used a combination of genetic operators and variable GA parameter values updated based on deterministic rules instead of using a fixed setting of predefined GA parameters throughout the evolutionary process. The experimental results of their approaches [182, 183] showed promising results. In the future, it may be possible to apply an artificial ecology on the evolutionary FMCRLD to further improve the efficiency and performance of the GA. Secondly, as mentioned in Section 3.1.2, finding a global optimum FMCRLD can be viewed as a complex multi-level optimisation problem. This research is focused on the upper level optimisation - a combinatorial optimisation problem of cavity grouping and layout design and associated runner layout design (i.e. FMCRLD). As demonstrated in case study I, if necessary, the optimum FMCRLD generated by the ICMLDS prototype can be further optimised by slightly adjusting the lengths of some runner segments associated with the positions of the corresponding cavities. This is lower level optimisation - a parametric optimisation of the lengths of runner segments[*] (see L_1 and L_2 in Figures 56a and 56b for example). In the future, a GA with standard fixed-length real number encoding[†] can be used to further optimise the optimum FMCRLD using the same fitness evaluation approach. Because of the use of standard encoding, standard genetic operators can be simply adopted. The existing program will be modified to allow overlapping boundary boxes and a new penalty function capable of handling the constraint of interference of moulding parts with a minimum offset distance (d) among parts (see Figures 56a and 56b).



(a) Before the lower level of optimisation **(b) After the lower level of optimisation**

Figure 56. Before and after the lower level optimisation

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[*] *The number of runner segments is determined by the optimum FMCRLD on the higher level.*

[†] *The length of the chromosome is equal to the number of runner segments. Each gene in the chromosome represents the length of each runner segments.*

6 SUMMARY OF INNOVATION AND RESEARCH VALUE

This chapter summarises the innovation and value of this research. The innovations in this research are highlighted in Section 6.1. The practical and academic values of this research are discussed in Section 6.2. The commercial value of this research is presented in Section 6.3.

6.1 Innovation in this research

Traditionally, FMCRLD is demanding and experience-dependent. Existing trial-and-error manual design methods result in human errors, and non-optimised and inconsistent FMCRLD in the supporting company. The nature of FMCRLD is non-repetitive and generative. In addition, FMCRLD optimisation can be viewed as a complex combinatorial layout design optimisation problem. Due to the nature and complexity of FMCRLD, traditional design automation and optimisation approaches are not applicable. Over the years, no commercial software package, patented system or research can support FMCRLD automation and optimisation. Inspired by the biological evolutionary design in nature, this research pioneered the application of the evolutionary design approach on FMCRLD automation and optimisation. The innovative concept of evolutionary FMCRLD using GA and SG was inspired by the theory of evolution in nature "Survival of the Fittest" and the biological genotype-phenotype mapping process of the generation of form in living systems. This innovative approach aims to automate and optimise such complex FMCRLD with an explorative and generative design process embodied in a stochastic evolutionary search. However, putting this innovative approach into practice is full of challenges. Firstly, the use of SG in the field of family mould design has never been proposed before. This research pioneered the study of FMCRLD and developed a novel SG of FMCRLD. Secondly, this research developed an innovative hybrid SG-based chromosome capable of representing complex and generative FMCRLD with minimal redundancy. Based on this innovative chromosome design, a new genotype-phenotype mapping algorithm integrated with the SG of FMCRLD and mould design knowledge was developed to generate valid chromosomes of individuals in the initial population. Thirdly, this research first developed a new group-oriented SG-based crossover operator that can inherit or combine meaningful features from both parents to reproduce stronger offspring without violation of design constraints and disruption of the useful parts (schemata) of the chromosome during recombination. In addition, three new types of mutation operators integrated with the SG of FMCRLD were also developed for introducing new species into the population without violation of the design constraints. Fourthly, filling balance is one of the most important performance goals in family mould design, but it is too costly and time-consuming to use such expensive mould flow CAE simulation programs to evaluate a large number of combinations of different FMCRLD alternatives in the GA search. In order to overcome this challenge, this research developed flow path balance performance measurement (P_f) and runner diameter balance performance measurement (P_r) to quantify the filling balance performance of FMCRLD without the aid of expensive and time-consuming mould flow CAE simulation. Finally, this research pioneered the design automation and optimisation of complex combinatorial FMCRLD in mould making industry by developing an innovative solution based on the nature-inspired evolutionary design approach.

6.2 Research value

This section aims to discuss the practical contributions of this research to the supporting company and the academic value of this research in the fields of mould design and evolutionary design.

6.2.1 Contributions to the supporting company

From a business point of view, the supporting company can gain two major business benefits from this research. The first business benefit is that the supporting company can retain its customers and gain more profits by producing more error-free and optimised family moulds in less time with its existing limited design workforce through the advanced FMCRLD automation and optimisation. As demonstrated in the case studies, using the ICMLDS prototype, even less experienced mould designers can design error-free and optimised FMCRLD considering critical economic factors, family mould design objectives and constraints within minutes rather than hours. Not only does the ICMLDS prototype significantly speed up the design process and streamline the workflow starting from the early CMLD phase to the later detail design phase, it also frees up a lot of mould designers' time to further refine the design and make the right decisions at the beginning. Most importantly, using the ICMLDS prototype to perform FMCRLD can avoid the costly design defects (such as serious filling imbalance and violation of mould base size constraint) caused by human design errors, and thereby ensure on-time delivery of error-free family moulds for production. As mentioned in Section 1.3, this is essential for retaining existing customers and gaining profits.

Another important business benefit is that, through the use of the ICMLDS prototype, the supporting company can train more new and inexperienced mould designers to be proficient in family mould design in a more systematic and efficient way to ensure a stable and sufficient qualified and productive design workforce for future company growth. As demonstrated in the case studies, the rapid design visualisation and instant design feedback capabilities of the ICMLDS prototype enable less experienced mould designers to explore more what-if design scenarios in less time and to learn the art of family mould design by digital experimentation in an intelligent and interactive design environment.

In conclusion, the ICMLDS prototype can boost mould designers' ability and productivity in performing FMCRLD during the CMLD phase. This research successfully developed a powerful intelligent design tool as well as an interactive design-training tool capable of encouraging and accelerating mould designers' design alternative exploration, exploitation and optimisation for better design in less time. This research has totally innovated the traditional FMCRLD process with the groundbreaking evolutionary FMCRLD approach in an effort to overcome the shortage of experienced mould designers and improve the supporting company's profit margin in today's highly competitive market. In addition, no existing commercial software package or patented system can support FMCRLD automation and optimisation in the market. This research can be commercialised to fill this market gap. The direct commercial values of this research are discussed in Section 6.3. Besides, the innovation of this research enables the supporting company to explore new business opportunities. Some potential business opportunities of this research are proposed in Chapter 7.

6.2.2 Contributions to knowledge

As discussed in Section 1.4, the majority of previous research work focused on the automation of other sub-design tasks for more simple and regular "One Product Moulds" while a study on FMCRLD has gained little attention over the years. Due to the nature and complexity of family mould design, a standard and information on FMCRLD is very limited. Research on FMCRLD automation and optimisation has never been studied before. This research focused on this topic in an effort to fill this critical knowledge gap. The innovation of this research has contributions to two major knowledge domains: mould design and evolutionary design. In the field of mould design, this research initiated a new and challenging research topic by introducing the art of FMCRLD and analysing the characteristics, complexity and functional requirements of FMCRLD automation and optimisation. In the field of evolutionary design, this research demonstrated the power of the evolutionary design approach using GA combined with SA in automating and optimising combinatorial and generative FMCRLD. The innovations of the hybrid SG-based chromosome design, genetic operator design and fitness evaluation provides a deeper insight into the art of evolutionary design and explores a new direction for research of complex combinatorial and generative layout design automation and optimisation. Future research inspired by the innovations of this research is proposed in Chapter 8.

6.3 Commercial value

As previously mentioned in Section 6.2.1, FMCRLD automation and optimisation is a critical market gap in the field of family mould. If this research can be commercialised, it may fill this market gap and create additional commercial value. This section focuses on discussing the future impact and possible commercial value of this research in the areas of (1) MCAD software market, (2) Computer-Aided Sculpting (CAS) software market, (3) Cost estimation software market and (4) Mould flow CAE software market.

6.3.1 MCAD software market for family mould design

In China, apart from the supporting company, there are about 1,500[*] mould shops and manufacturing companies which also use ProEngineer® MCAD software packages to design family moulds. In today's difficult business environment, other mould shops

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[*] *Based on the number of mould shops and manufacturing companies in the toy industry invited to attend the PTC user conference 2010 held in Shanghai, China.*

and manufacturing companies are also facing the same business challenges, such as the shortage of experienced mould designers and the rising material and labour cost in China. In addition, as discussed in Section 4.1, the comprehensive literature review shows that no existing commercial MCAD software packages [18-35] and patented system [14, 17] can support FMCRLD automation and optimisation. Therefore, a third-party application program for FMCRLD automation and optimisation has strong market potential in China. For reference only, a list price of an optional mould design software package [22] for ProEngineer® Wildfire™ 4.0 is about US$10,000[*] per license, but this optional mould design software package cannot support FMCRLD automation and optimisation. If the ICMLDS can be successfully commercialised and sold to the 1,500 potential customers, it will be a US$10 million software business.

In this research, the ICMLDS prototype has already been developed as a third-party application program seamlessly embedded into the advanced commercial MCAD software package – ProEngineer® Wildfire™ 4.0. However, it may take about eight months to one year to finish the further work (as mentioned in Section 5.5) and convert the prototype into a final commercial software package. Besides, additional

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[*] *Based on a PTC's quotation of an optional mould design software package for ProEngineer® Wildfire™ 4.0 requested by the supporting company in 2010.*

software research and development, marketing and technical support teams are required. Therefore, the supporting company should start up a new software business division to develop and market this innovative ICMLDS software product, targeting the high profit niche MCAD software market.

Similarly, the evolutionary FMCRLD approach can also be implemented and embedded into other advanced commercial MCAD software packages [21, 27, and 28] with their own API toolkits. Therefore, this research can be easily commercialised to fill the market gap for family mould design and benefit the whole mould making industry. In addition, the combination of the power of evolutionary design using GA and SG with an advanced 3D parametric modelling capability of the commercial CAD software package reveals great commercial potential to be an innovative solution for engineering design automation and optimisation in the future. Some new application areas are explored in Chapter 8.

6.3.2 Computer-Aided Sculpting (CAS) software market for family mould design

Traditional MCAD systems cannot deal with complex, highly detailed and organic shapes for toys like action figures. Since the Computer-Aided Sculpting (CAS) technology became available on the market, many major toy makers, including Mattel®/Fisher-Price®, Playmobil® and Hasbro®, have been using this CAS technology to create 3D digital sculptural models for toys instead of making physical prototype models. This CAS technology totally innovates the traditional workflow starting from design to mould making in the toy industry. Recently, the latest Sensable® 3D touch-enable Freeform® version 11 modelling system [184] has introduced a new function for faster prepping of models for rapid manufacturing and tooling. Figure 57 shows the original finished model with high-resolution model pieces. Repositioning these model pieces for a mould layout is a time-consuming and tedious task because users need to reposition each of the pieces in this high-resolution model one by one manually. The new repositioning function allows users to easily position low-resolution copies of the model pieces to quickly decide the most efficient layout for the family mould (see Figure 58).

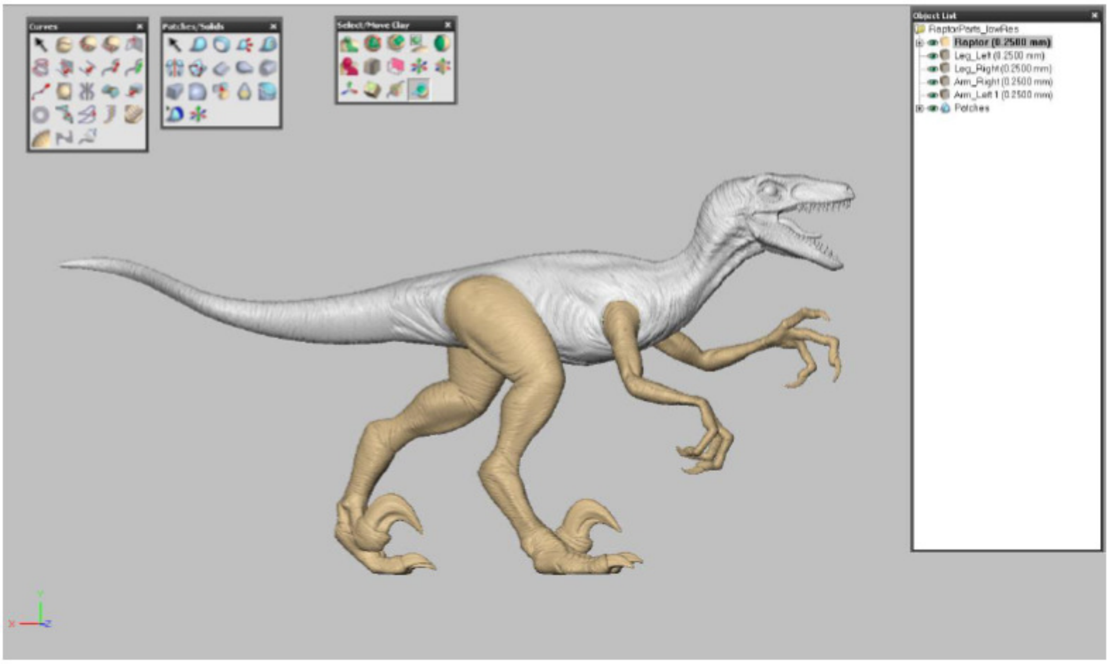


Figure 57. The original finished model with high-resolution model pieces [184]

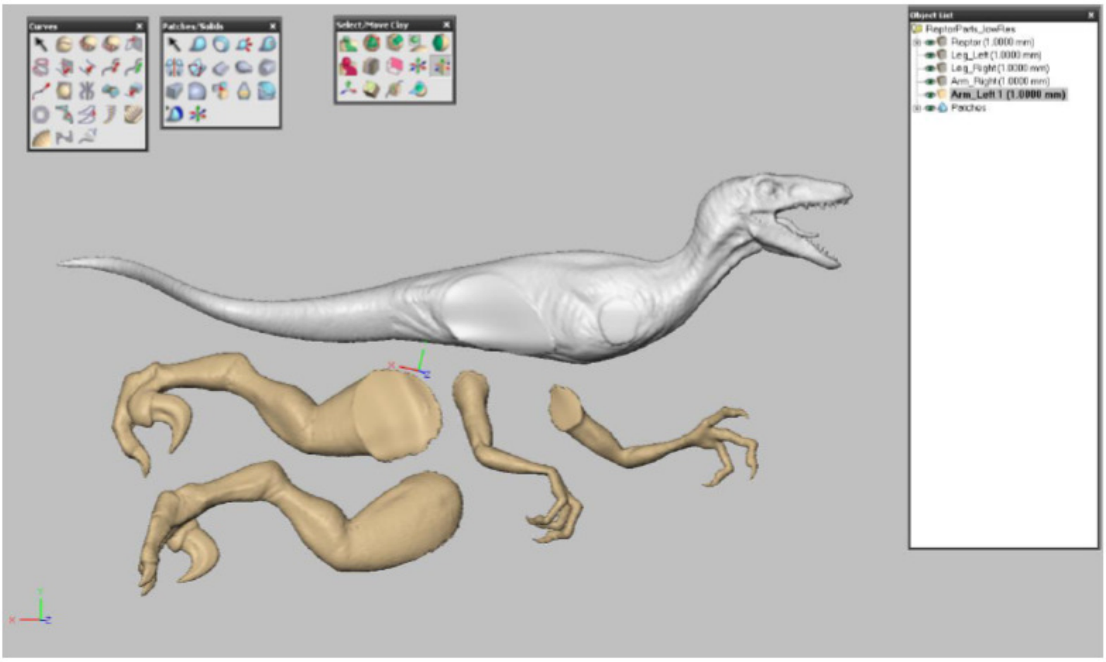


Figure 58. Repositioning the low-resolution copies of the model pieces [184]

However, it still requires users to determine the mould layout and move the low-resolution model pieces one by one manually. If the evolutionary FMCRLD approach can be integrated with this repositioning function of the Freeform® modelling system, it can determine the best FMCRLD and generate the mould layout automatically for downstream production. Combining the power of the evolutionary FMCRLD approach with the advanced sculptural modelling capability of Freeform® can further innovate the workflow in the toy industry.

6.3.3 Cost estimation software market for family moulds

The efficiency and accuracy of cost estimation of family moulds largely rely on a quick and good FMCRLD decision made in the early quotation stage. However, no existing commercial software package [8-12] or patents [13, 15, and 16] can support automatic cost estimation of family moulds based on optimum FMCRLD solutions. The ICMLDS can automatically generate multiple optimum FMCRLD solutions for users to select the best trade-off solution between performance and cost. Accordingly, the cost components (such as C_n, C_m, C_r, C_s and C_j) of each optimised solution are calculated for fitness evaluation beforehand. These cost components determine the critical cost of a family mould. If the approximate manufacturing cost of each dissimilar cavity in a family mould can be input by the users or automatically estimated using other techniques [41-47] for estimating the mould manufacturing cost of a single cavity, this ICMLDS prototype can be commercialised not only as an intelligent design tool but also as an innovative cost estimation solution to fill the market gap in the area of cost estimation of family moulds.

6.3.4 Mould flow CAE software market for filling balance optimisation of family moulds

The literature review (see Section 1.4) shows that existing commercial mould flow CAE software packages [36, 37] cannot perform automatic artificial filling balance considering the global optimisation of cavity layout, runner lengths and diameters simultaneously. As mentioned in Section 5.2, even an experienced mould flow CAE engineer cannot achieve the global optimum artificial filling balance solution unless a good FMCRLD is provided. The ICMLDS prototype can provide the best FMCRLD for mould flow CAE engineers to achieve the global optimum artificial filling balance in the early mould design phase, saving a huge amount of time and money spent on performing artificial filling balance on numerous different FMCRLD alternatives. If the evolutionary FMCRLD approach can be seamlessly integrated with the existing commercial mould flow CAE software packages, it will become a powerful automatic design and analysis tool for solving the complex problem of the global optimisation of artificial filling balance of family moulds in industry.

7 POTENTIAL BUSINESS OPPORTUNITY

This chapter aims to explore more business application fields in relation to family mould design. Firstly, the impact of this research on the market of rapid prototype injection moulding parts is discussed in Section 7.1. Secondly, the idea of application of this research on the production of high precision injection moulding parts in prototype and low-volume production quantities is introduced in Section 7.2. Finally, the value of combining the Tandem® mould technology with this research is discussed in Section 7.3.

7.1 Application of evolutionary FMCRLD on rapid prototype injection moulding parts

The rapid growth of the Quickparts® Company [12] and Protomold® Company [14] highlights the rise of the market of rapid prototype injection moulding parts. They have successfully created a new online business model in the traditional mould making industry by introducing an instant online quotation system, real-time order status and shipment tracking, fast delivery of rapid prototype injection moulding parts and so forth. They still cut the mould with traditional Computer Numerical Control (CNC) machines, but they can deliver the prototype injection moulding parts to their customers on the next business day because they automate the quotation, mould design, CNC programming and production scheduling. As discussed in Section 1.4, the patented system [14] developed by the Protomold® Company makes use of the economic advantages of traditional family moulds to produce dissimilar moulding parts for multiple customers in a single mould block, saving material cost and machining step up time. However, this company's aluminium prototype family moulds are limited to producing not more than 5,000 simple straight-pull parts. Moreover, the patented system cannot determine an optimum family mould design for achieving better quality of moulding parts with less cost considering the critical design objectives and constraints for production, such as filling balance performance, cost of runner, mould base size and so forth. By comparison, this research has achieved a more advanced FMCRLD automation and optimisation capable of designing different types of family moulds satisfying a wide range of customers' requirements from prototyping to high-volume production. In addition, as proposed in Section 6.3.2, the existing ICMLDS prototype can be further developed to support rapid automatic quotation of family moulds. If the ICMDLS can be integrated with the supporting company's web-based Product Lifecycle Management (PLM) system

(Windchill® from PTC) and an in-house developed shop floor production management system, it will be possible to develop a total solution capable of providing an instant automatic quotation service, online job status reporting and fast delivery of production moulds and prototype moulding parts to customers. This research can provide a previously unavailable capability for the supporting company not only to innovate the existing traditional mould making business but also to expand into the rising market of rapid prototype injection moulding parts.

7.2 Application of evolutionary FMCRLD on high precision injection moulding parts

Traditionally, family moulds have not been acceptable for high precision applications due to the difficulties of balancing dissimilar cavities. Family moulds have been largely limited to low tolerance parts over the years. However, this will no longer be a limitation if all dissimilar parts of a family mould can be direct-gated and perfectly balanced with advanced Dynamic Feed® hot runner technology, originally developed by Kazmer et al. [185]. The Dynamic Feed® hot runner system can provide real time closed loop pressure control to each dissimilar cavity independently, achieving tight dimensional control of each moulding part regardless of the dissimilar cavity geometries and sizes in a family mould [186]. However, the major drawback of incorporating this dynamic feed system in a traditional family mould is the high start-up cost (approximately US$60,000 for a typical 4-drop mould). Therefore, it is not economic to build such expensive stand-alone dynamic feed hot runner family moulds only for one-off low-volume production of high precision injection moulding parts, not to mention for prototype quantities. However, if the expensive dynamic feed hot runner system can be reused for a number of different low-volume or prototype mould projects over and over again, the combination of the dynamic feed hot runner technology with the family mould concept will become a flexible and cost-effective solution. As implemented in case study II, the mould cavity for each dissimilar part was manufactured as an individual mould block, instead of incorporating all cavities in a single mould block. In the aspect of the modular tooling concept, these individual mould blocks for dissimilar parts can be viewed as flexible modular tooling components manufactured for different products for different customers sharing the same mould base and the expensive dynamic feed hot runner system. As shown in Figure 59, the 4-drops dynamic feed hot runner system is incorporated in the universal "quick-change" mould base capable of producing different moulding parts with four interchangeable mould inserts at once. Each interchangeable mould insert module can be regarded as an individual small mould sub-assembly having its own cavities, runners, cooling circuit, sliders, ejectors and cavity pressure sensors, while the hot runner drop can be viewed as a hot runner nozzle for each small mould. This highly flexible modular mould combined with dynamic feed hot runner technology can offer faster lead times on tooling, lower tooling costs and better operational efficiency [187].

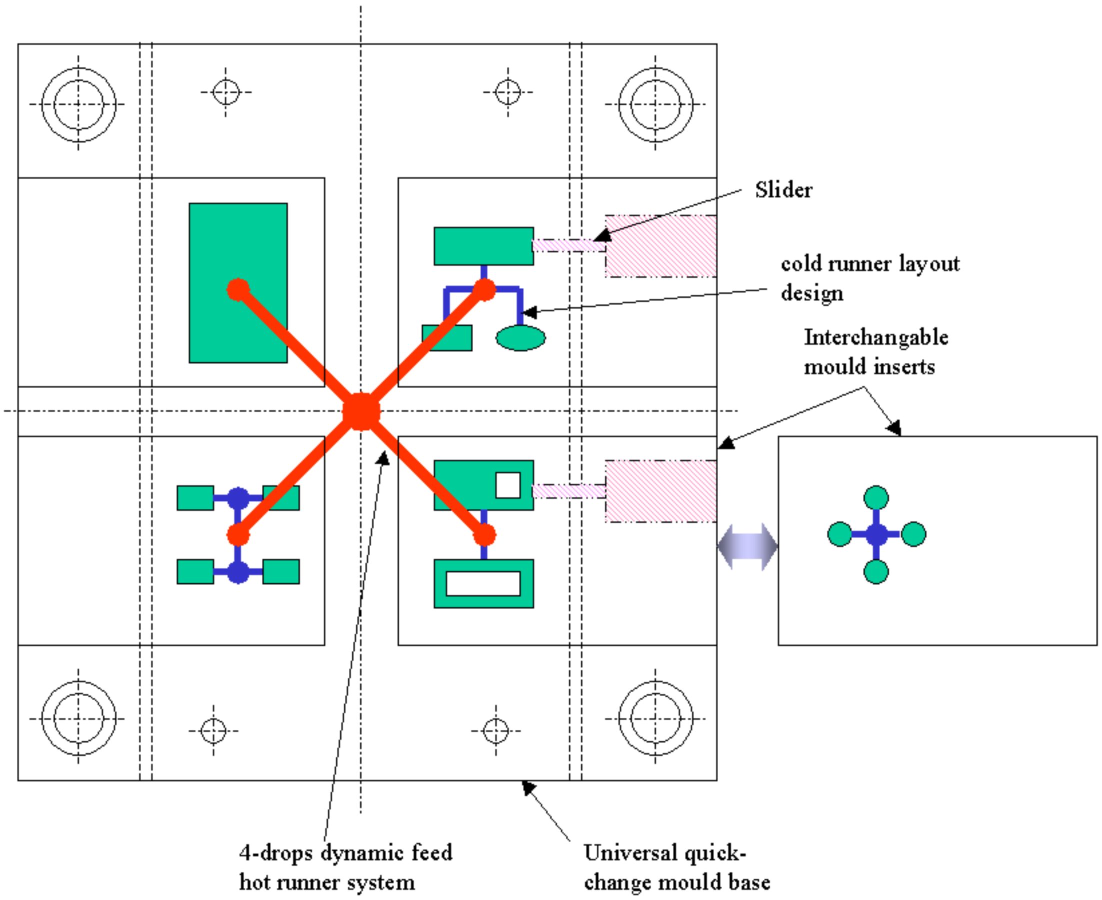


Figure 59. The modular tooling concept

In today's highly competitive market, time to market is extremely important. As mentioned in Section 7.1, the markets of rapid prototype and low-volume production of injection moulding parts are rising. High-technology applications like telecommunication and consumer electronic products are challenged by a short product life, demanding fast delivery of high quality injection moulding parts with high precision and high cosmetic standards. High-value low-volume applications like medical devices and industrial equipment need tight tolerance injection moulding parts with no geometry limit for building and testing a rapid working prototype to reduce the time to market and ensure the high quality and reliability of the product before real production. In this research, the existing ICMLDS can be further developed and customized to support dynamic feed hot runner modular mould design automation and optimisation (see Section 8.1.1). The combination of innovation of this research and the advantages of dynamic feed hot runner modular tooling offers a great opportunity for the supporting company to expand the high value-added market of high precision injection moulding parts.

7.3 Application of evolutionary FMCRLD on Tandem® moulds

Tandem moulds [188] can be viewed as alternatively opening stack moulds having two parting levels allowing for alternatively filling and subsequently de-moulding during the operational cycle (see Figure 60). Especially when the cooling times are relatively long, this alternative moulding process of a tandem mould can make use of the idle time to perform other moulding tasks on another parting level to increase the productivity like merging two moulds into one.

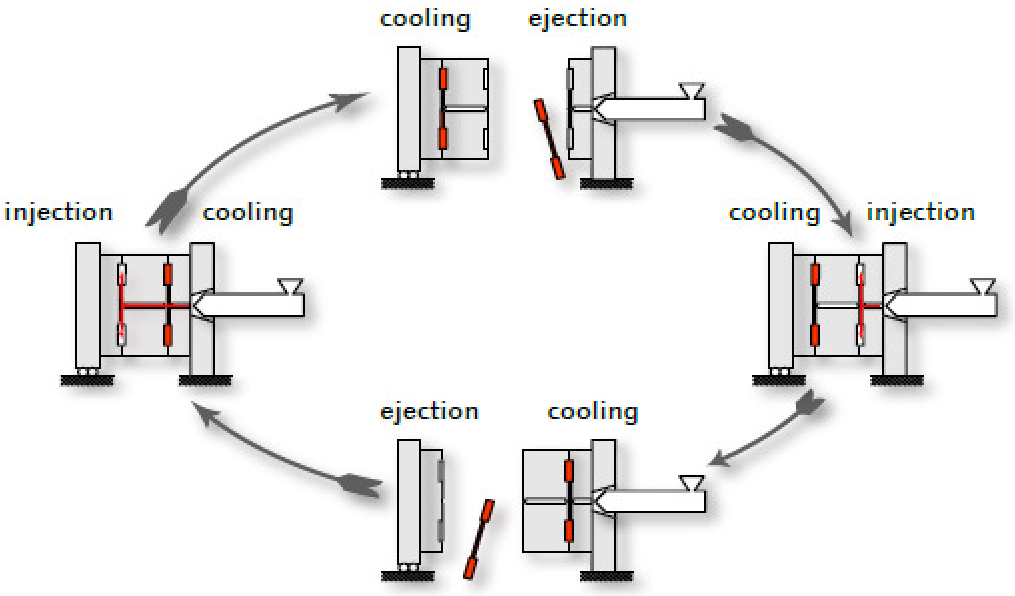


Figure 60. The operation cycle of a tandem mould (courtesy: T/mould Solution GmbH & Co. KG)

Tandem moulds can be used to produce dissimilar moulding parts using the individual parting levels, whereby parameters can be set individually for each dissimilar moulding part. If this tandem mould concept is combined with the dynamic feed hot runner modular mould (as previously introduced in Section 7.2), it can achieve the double output within the same cycle time as in the standard mould. The existing ICMLDS can be further developed and customized to support dynamic feed hot runner tandem modular mould design automation and optimisation (see Section 8.1.1).

8 PROSPECTS FOR FUTURE RESEARCH

Inspired by the innovation of this research, this Innovation Report attempts to expand research opportunities of the evolutionary design approach using GA and SG into a wide variety of new areas of engineering design automation and optimisation ranging from hot runner layout design, ejector layout design and cooling layout design to architectural space layout design.

8.1 Mould design

As mentioned in Section 1.4, apart from FMCRLD, there are other market gaps and knowledge gaps in the areas of hot runner layout design, ejector layout design and cooling layout design. In an attempt to fill these gaps, this section provides prospects for future research on these areas based on the concept of the innovative evolutionary design approach using GA and SG developed in this research.

8.1.1 Hot runner layout design automation and optimisation

As previously mentioned in Sections 7.2 and 7.3, family mould design combined with dynamic feed hot runner technology and "quick-change" modular moulds and the Tendam® mould concept has potential business value. However, the literature review (see Section 1.4) shows that no research, commercial software packages or patented system can support hot runner layout design automation and optimisation for family moulds. Although this research focused on cold runner family mould, the existing evolutionary FMCRLD approach can be extended to support hot runner layout design automation and optimisation for family moulds. For example, as previously suggested in Section 5.5, the set of new SG rules of cold runner layout design for pin-point gates can be modified and integrated with hot runner design knowledge to synthesise hot runner layout design (see Figure 61).

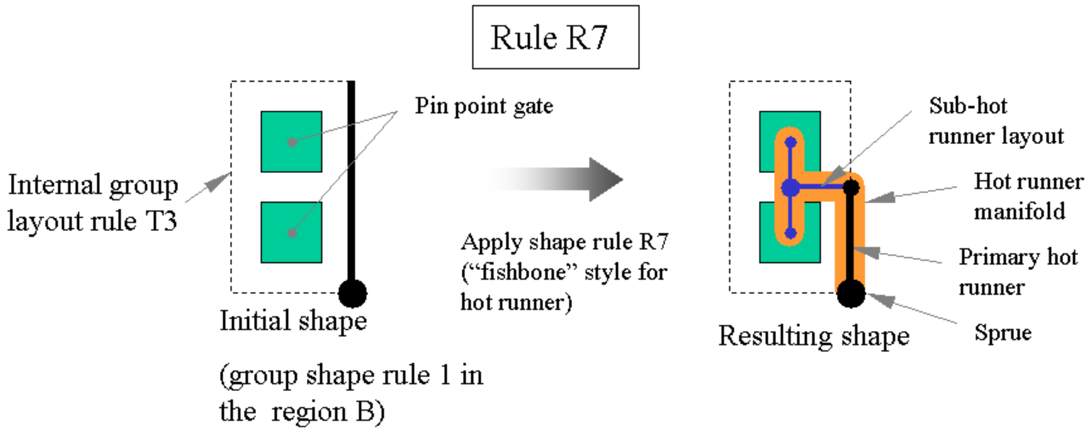
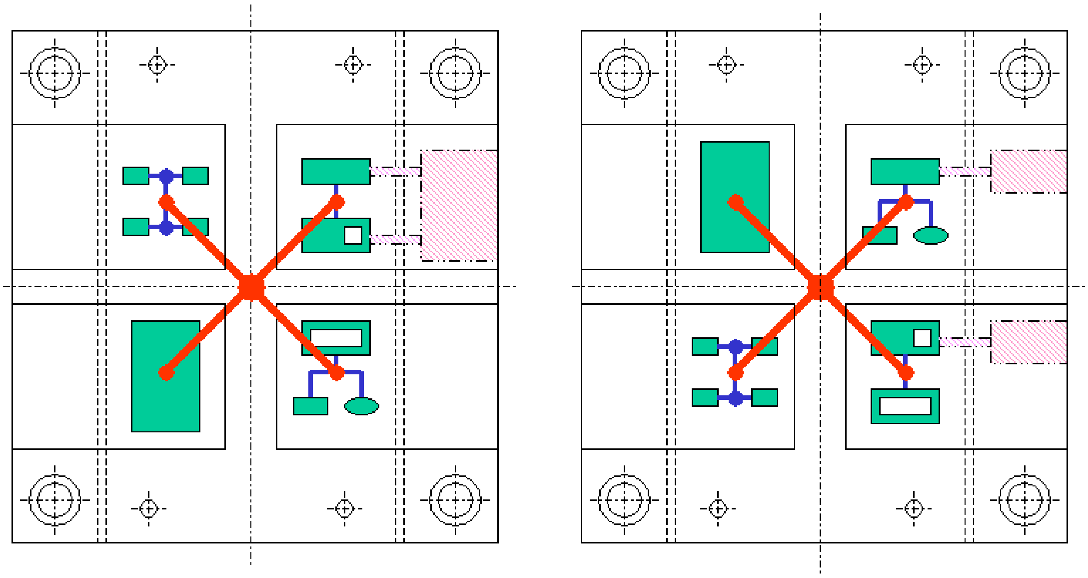


Figure 61. An example of a SG rule of hot runner layout design

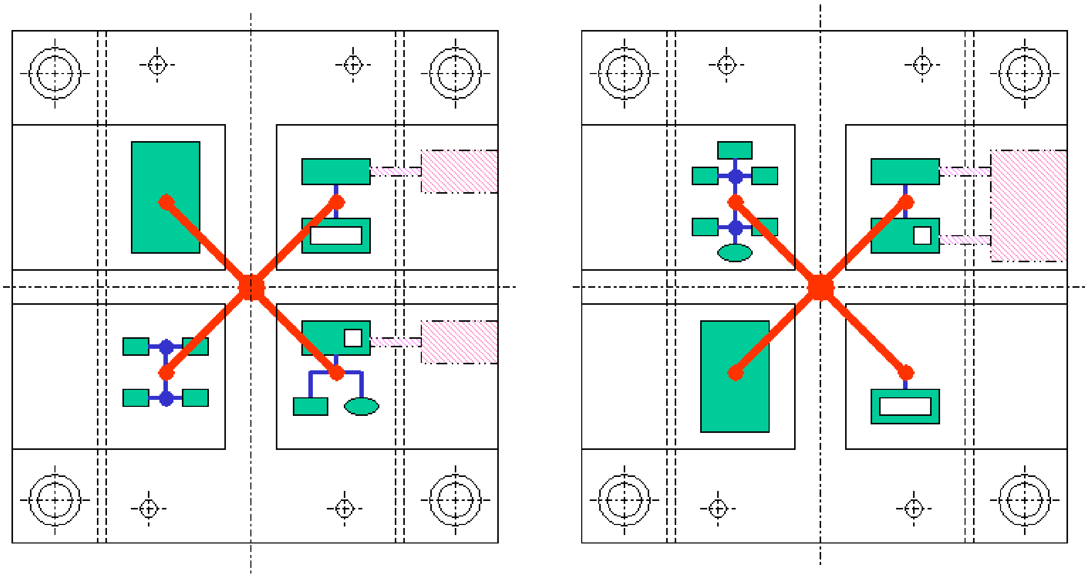
In general, the existing fitness evaluation function developed in this research can be reused, but the estimated cost of the hot runner system must be added to the cost function. Besides, the existing rule for selecting the mould base must also be modified to accommodate the hot runner assembly. Then the ICMLDS will be able to search for the global optimum cavity and hot runner layout design of a family mould considering a number of design objectives and constraints in relation to both hot runner layout design and family mould design. Combining the powerful parametric modelling capability of the existing CAD system and a comprehensive CAD model library of standard hot runner components, it is possible to customise the ICMLDS to automatically generate an optimum dynamic feed hot runner family mould layout design.

With regard to dynamic feed hot runner modular mould design automation and optimisation, it also can be viewed as a complex combinatorial FMCRLD optimisation problem. For example, Figure 62 shows some examples of a large number of possible layout design alternatives for a dynamic feed hot runner modular mould. In the case of ordinary 4-drops hot runner module tooling (single parting level), the number of cavity groups is fixed at 4. Accordingly, the algorithm for generating the initial population can be used to generate the fixed cavity group layout and the primary hot runner layout. The existing chromosome design and the SG rules can be reused, but genetic operations on the gene for storing the group layout rule number in the group session are omitted. Each cavity group can be viewed as a smaller mould accommodated inside a bigger mould base. The usable area of the smaller mould is fixed. Therefore, a new penalty function for handling the constraints of oversized cavity groups should be added to the fitness evaluation function. Besides, the algorithm for grouping sliders should consider the grouping of sliders for each cavity group instead of each side of the mould. In the case of 8-drops tandem modular tooling (two parting levels and 4-drops on each level), the number of cavity groups should be fixed at 8. For example, cavity groups 1-4 are on level 1 while cavity groups 5-8 are on level 2. A new set of runner layout SG rules also needs to be added for generating runner layout on different parting levels. Then the evolutionary FMCRLD approach can automatically determine the best cavity grouping and runner layout design for each interchangeable mould insert.



(a) Mould layout alternative 1

(b) Mould layout alternative 2



(c) Mould layout alternative 3

(d) Mould layout alternative 4

Figure 62. Some possible layout design alternatives of a dynamic feed hot runner modular mould

In conclusion, no research, existing commercial MCAD software package or patented system can support hot runner layout design automation and optimisation. Based on the aforementioned approach, the ICMLDS prototype can be further developed to realise design automation and optimisation of dynamic feed hot runner family moulds and "quick-change" modular moulds (single parting level or tandem). This further research enables the supporting company to explore new business opportunities in the high-value market of high precision injection moulding parts in prototype and low-volume production quantities.

8.1.2 Ejector layout design automation and optimisation

A proper ejector layout design is very important in mould design because a bad ejector layout design can cause part deformation and damage. Traditionally, mould designers usually determine the number, location and size of ejector pins on the basis of empirical rules based on mould designers' know-how, often resulting in part deformation and damage. Therefore, mould designers tend to use an excessive number of ejector pins, leading to a higher mould cost and less effective area for the cooling channels. Over the years, no commercial software package or patented system can support ejector layout design automation and optimisation. Research on this topic is still limited. Wang et al. [87] developed a balancing algorithm to optimise the arrangement and selection of ejectors in the ejection system of injection moulds. More recently, Kwak et al. [88] proposed a new method to compute the distribution of the necessary ejecting forces and transform the ejecting forces into a certain number of representative forces by a wavelet transform. Then the location and size of ejector pins are fine-tuned using a rule-based system. However, their research [87, 88] still cannot determine the optimum number of ejector pins. Ejector layout design automation and optimisation is full of challenges.

Similar to the characteristics of FMCRLD, the nature of ejector layout design is also generative and non-repetitive because different moulding parts with different features, sizes and geometries require different ejector layout designs. With regard to the optimisation complexity, like FMCRLD, ejector layout design can also be viewed as a complex multi-level optimisation problem with multiple design objectives and constraints. The upper level optimisation involves the determination of the optimum number and location of ejector pins. On the lower level, it is a parametric optimisation of ejector sizes. For these reasons, the evolutionary design approach using GA and SG also has great potential to support ejector layout design automation and optimisation. For example, using the similar development methodology used in this research, a comprehensive SG of ejector layout design integrated with the ejector layout design knowledge can be developed by studying the art of ejector layout design. For example, if there is a rib, two ejector pins should be located near the rib with a specific offset distance and location according to the size of the rib. If there is a boss with a depth of over 15mm, an ejector sleeve should be placed below the boss. In SG, the feature (such as rib, boss and flat surface) can be treated as an initial shape. A shape rule can be applied to the initial shape to control the placement and type of ejector (pin, sleeve or stripper plate). Similar to the concept of virtual cavity groups used in this research, the moulding part can be divided into different regions (groups) at random. Each region contains different sets of the aforementioned features. Based on this approach, a large number of possible ejector layout design alternatives can be synthesised with different combinations of regions associated with different sets of features. The hybrid SG-based chromosome can be customised to represent the ejector layout design with multiple sessions of ejector type, size, grouping and SG rules. Then the special genetic operators also need to be customised to reproduce stronger offspring and introduce new species without violation of design constraints and disruption of the useful schemata of the chromosome during the evolutionary process. With regard to fitness evaluation, the concept of the Cost Performance (CP) objective function can be reused. For example, the cost of each ejector layout design alternative can be calculated as the total cost of all ejectors. The ejection force balance performance can be used to evaluate how well the design can push off the moulding parts evenly. It can be quantified by calculating the centre of the resulting ejecting forces acting on all ejectors located in different locations with respect to the centre of a mould.

In conclusion, no commercial MCAD software package or patented system can support ejector layout design automation and optimisation. Research on this topic has gained little attention over the years. The proposed evolutionary design approach using GA and SG for ejector layout design automation and optimisation has never been proposed before. This innovative evolutionary design approach may reveal a new opportunity to realise ejector layout design automation and optimisation in practice. Further research in this area is highly recommended.

8.1.3 Cooling layout design automation and optimisation

Similar to FMCRLD, cooling layout design is demanding and experience-dependent. Although many research papers on cooling design [73-85] have been published, research on cooling layout design for family moulds has gained little attention over the years. Most research on automatic cooling layout design [82-85] has been focused on designing a single cooling circuit for a single moulding part only. In designing a cooling layout for family moulds, an individual cooling circuit for each dissimilar cavity can allow process engineers to adjust individual mould cavity temperature for additional level of injection process control. Li et al. [85] proposed a GA approach with a mixed variant-length chromosome (order-based encoding combined with real-number encoding) and ad hoc genetic operators to optimise the topological connection and geometric position of a cooling system. Their experimental result initially verified the feasibility of the GA approach for determining the optimum topological connection and geometric position of a cooling system. However, the optimisation result depends on a preliminary cooling layout design given by mould designers. In other words, their approach cannot support generative cooling layout design automation and optimisation.

By comparison, FMCRLD and cooling layout design have some common characteristics. Both of them are generative and non-repetitive. Different moulding parts having different shapes, sizes and features require different cooling circuits. Different cavity layout combinations of dissimilar moulding parts in a family mould result in a number of possible combinations of different topological structures of the cooling system. The solution space is very large. Therefore, optimisation of cooling layout design can also be viewed as a complex multi-level optimisation problem with multiple design objectives and constraints. On the upper level, it is a complex combinatorial optimisation of the topological structure of the cooling system involving the determination of the optimum number, location and connection of cooling channels. On the lower level, it is a parametric optimisation of the cooling channel sizes. In this case, the evolutionary design approach using GA and SG has great potential to automate and optimise such complex cooling layout design for family moulds with its explorative and generative design process embodied in a stochastic evolutionary search. For example, a comprehensive SG of cooling layout design integrated with the cooling system design knowledge can be developed to automatically generate a number of possible preliminary cooling lines adapting to the feature and geometry of the moulding parts. This set of cooling lines for the individual moulding part can be handled as a cooling circuit group like the virtual cavity group used in this research. The hybrid SG-based chromosome can be customised to encode the cooling layout design with multiple sessions storing the different types of genetic information, such as type (inlet, outlet and separator), drilling direction, cooling circuit grouping and SG rules. This hybrid SG-based chromosome design can simplify the search space because the SG rules can handle the complicated geometry information of cooling channels and generate feasible solutions. It enables the GA to explore and exploit the feasible solution space efficiently. The group-oriented genetic operators integrated with the SG can be customised to reproduce stronger offspring, which inherit meaningful ‘building blocks’ from both parents, and to introduce new species without violation of design constraints during the evolutionary process. The fitness evaluation of a candidate cooling layout design can be obtained by a fuzzy evaluation approach previously developed by Li et al. [83]. This fuzzy weighted average can quantify the cooling performance, the manufacturability and the structure strength of a candidate cooling layout design, and allow mould designers to bias the fitness evaluation towards a specific design requirement by specifying the importance level for each weighting. After the optimum cooling layout design is determined, the cooling channel sizes can then be further optimised by mould flow CAE engineers based on the mould cooling analysis results with the aid of commercial mould flow CAE software packages [36, 37].

In conclusion, cooling layout design automation and optimisation is a challenging research topic. Over the years, no research, commercial software package or patented system has been able to support it. In the area of injection mould cooling design research, the evolutionary design approach has never been proposed before. It shows great potential to provide a previously unavailable capability to automate and optimise such complex cooling layout design. Further research in this area is highly recommended.

8.2 Architectural space layout design

As mentioned in Section 3.2.3, architectural space layout design is the process of allocating a set of space elements and designing topological and geometrical relationships between them according to certain design criteria [149]. Therefore, both FMCRLD and architectural space layout design have some common design characteristics and challenges. Both of them are complex, combinatorial, non-repetitive and human-dependent. Although research on the evolutionary design approach using GA and SG for family mould design is new, research on the evolutionary design approach for architectural space layout design [162, 163] has gained more attention. However, the hybrid SG-based chromosome and group-oriented SG-based genetic operators have never been proposed in the field of architectural design. Some function-oriented architectural space layout design projects (such as for hospitals, factories and airports) involve not only designing topological and geometrical relationships but also combinatorial grouping problems among space elements. For example, different grouping of functional departments in a hospital, facilities in a factory, and functional areas in an airport affect their working capacity and workflow efficiency. By analogising the FMCRLD to the architectural space layout design, the cavity group can be viewed as a room, department or a group of facilities. The runner network connecting all cavities can be considered the travelling path network connecting all departments or work groups, or a HVAC (Heating, Ventilation and Air Conditioning) routing network in the building. The mould base size constraint can be regarded as a limitation of the usable area in the construction site. This research pioneered an evolutionary design approach for solving a complex combinatorial space layout design problem using the hybrid SG-based chromosome and group-oriented SG-based genetic operators that may inspire a new research direction to automate and optimise the function-oriented architectural space layout design using GA and SG.

9 CONCLUSIONS

This research highlights that FMCRLD is the most demanding and critical task that determines the cost and performance of a family mould in the early CMLD phase. Facing the challenges of increasing costs of material and labour, and the shortage of experienced mould designers, traditional experience-dependent manual FMCRLD workflow cannot achieve the major business goals – retain existing customers and gain profits by producing family moulds faster, better and cheaper with its limited design workforce. In order to overcome the aforementioned business challenges and achieve the business goals, a computer-based design tool for supporting FMCRLD automation and optimisation is urgently needed. However, no previous research, existing commercial software packages or patented technologies can support FMCRLD automation and optimisation. FMCRLD automation and optimisation is the critical market gap and knowledge gap in the field of mould design.

This research characterises that the nature of FMCRLD is non-repetitive and generative. The complexity of FMCRLD optimisation involves solving a complex two-level combinatorial layout design optimisation problem with a dynamic changing number of variables, multiple mould design objectives and constraints. The upper-level optimisation is a combinatorial optimisation problem of FMCRLD while the lower-level one is a parametric optimisation of runner sizes (the number of variables is determined by the FMCRLD). The solution space is so large that traditional design automation and optimisation techniques cannot deal with it efficiently. Inspired by the theory of evolutionary design in nature "Survival of the Fittest" and the biological genotype-phenotype mapping process of the generation of form in living systems, this research first proposed the innovative evolutionary design approach for FMCRLD automation and optimisation using GA and SG. This nature-inspired evolutionary FMCRLD approach aims to automate and optimise such generative and complex FMCRLD with its explorative and generative design process embodied in a stochastic evolutionary search. However, putting this innovative approach into practice involves challenges in designing the SG of FMCRLD, chromosome, genetic operators and fitness evaluation. This research pioneered the study of the art of FMCRLD and developed a comprehensive SG of FMCRLD integrated with mould design knowledge domain that can synthesise a large number of feasible FMCRLD alternatives in a generative way. Based on the SG of FMCRLD, this research developed the hybrid SG-based chromosome capable of encoding complex and generative FMCRLD with minimum redundancy. The specially designed group-oriented SG-based genetic operators enable the GA to reproduce stronger offspring which inherit meaningful features from both parents and introduce new species into the population without violation of design constraints and disruption of the useful parts of the chromosome. With regard to the fitness evaluation, this research developed a flow path balance performance measurement (P_f) and runner diameter balance performance measurement (P_r) to quantify the filling balance performance of FMCRLD without using computer-intensive mould flow CAE analysis. Based on this innovative evolutionary FMCRLD approach, the ICMLDS prototype seamlessly embedded within the advanced commercial MCAD system was successfully developed and implemented in the supporting company.

The ICMLDS prototype was verified by a team of the supporting company's experienced mould designers and mould flow CAE engineers through three case studies. The implementation and verification results showed that the ICMLDS prototype could eliminate human errors and boost mould designer's ability and productivity in performing FMCRLD during the CMLD phase. The evolutionary design, rapid design visualisation and instant design feedback capabilities of the ICMLDS prototype enable less-experienced mould designers to learn the art of family mould design by exploring more what-if design scenarios in less time. In summary, the ICMLDS prototype has been proven to be a powerful intelligent design tool as well as an interactive design-training tool that can encourage and accelerate mould designers' design alternative exploration, exploitation and optimisation for better design in less time. However, due to the limited time frame and the scope of this research, some limitations of this research need to be addressed in the future. Firstly, the existing ICMLDS prototype cannot support pin-point gate design and hot runner design because the majority of family moulds produced in the supporting company are cold runner and single side gate. However, this limitation can be overcome by adding a new set of SG runner layout rules to support pin-point gate design and hot runner design. Secondly, the accuracy of the relative variation of CFP lengths of dissimilar cavities in a family mould still highly depends on individual mould designer's estimation, affecting the P_f evaluation and thereby the optimisation results. Further work on automatic estimation of CFP length of a moulding part is needed. Thirdly, the simple weighted sum approach adopted in this research may bury the significance of each individual criterion. Further work on establishing a systematic method for determining weightings is needed. Besides, the general GA parameter setting used in this research may not work well for other cases. Mould designers may need to adjust the parameters and rerun the program repeatedly until satisfactory results are obtained. In the future, this problem may be solved by applying an artificial ecological on the evolutionary FMCRLD to achieve a self-adaptive setting of

GA parameters. Finally, this research cannot automatically adjust the cavity positions and the lengths of runner segments to further optimise the design based on a given FMCRLD. Further work on this lower-level optimisation using a simple GA coupled with a fixed-length real number encoding is recommended.

From a business point of view, this research has totally innovated the old-fashioned manual FMCRLD workflow with the groundbreaking evolutionary FMCRLD approach to overcome the supporting company's business challenges and achieve its major business goals. The major business benefits of the research outcomes are summarised as below:

- The advanced FMCRLD automation and optimisation enables less experienced mould designers to produce error-free and optimised FMCRLD within minutes rather than hours. This research outcome enables the supporting company to:
    - Increase output with its existing limited design workforce by increasing its design ability and productivity
    - Eliminate costly consequences of major design defects and retain existing customers by ensuring on-time delivery of error-free family moulds

- The rapid design visualisation and instant design feedback capabilities of the ICMLDS prototype enable less experienced mould designers to explore more what-if design scenarios in less time and to learn the art of family mould design by digital experimentation in an intelligent and interactive design environment. This research outcome enables the supporting company to:
    - Train more new and inexperienced mould designers to be proficient in FMCRLD systematically and efficiently
    - Ensure a stable and productive design workforce for future company growth

To generate additional commercial values, the ICMLDS prototype can also be customised and commercialised to fill the market gap in the areas of MCAD software market, cost estimation software market and mould flow CAE software market regarding family mould design. Most importantly, this research can provide a previously unavailable design automation and optimisation capability for the supporting company to expand the traditional cold-runner family mould market into the rising market of rapid injection moulding parts for a wide variety of customers' requirements ranging from prototype, low-volume batch production to high-volume production. Besides, this research also suggests that the evolutionary FMCRLD approach can combine with dynamic feed hot runner technology, "quick change" module mould and/or tandem mould technology enabling the supporting company to explore new business opportunities in the high-value low-volume market (such as telecommunication, consumer electronic and medical devices) of high precision injection moulding parts in prototype and low-volume production quantities. With regard to the contributions to knowledge, this research provides a deeper insight into the art of evolutionary design for complex combinatorial layout design automation and optimisation. The innovation of this research expands research opportunities of the evolutionary design approach into a wide variety of new application areas including hot runner layout design, ejector layout design, cooling layout design and architectural space layout design.

REFERENCES

[1] China Market News, *Asia Mould and Die 2005*, Vol. 11, pp. 50-51

[2] G. Menges, W. Michaeli and P. Mohren, (1986), *How to make Injection Moulds* (3rd Edition), ISBN 1-56990-282-8, Hanser, Cincinnati

[3] Herbert Rees, (2002), *Mould Engineering*, ISBN 1-56990-131-7, Hanser, Cincinnati

[4] Herbert Rees and Bruce Catoen, (2006), *Selecting Injection Moulds: weighing cost vs. productivity*, ISBN 1-56990-389-1, Hanser, Cincinnati

[5] Robert A. Malloy, (1994), *Plastic part design for injection moulding: an introduction*, ISBN 1-56990-129-5, Hanser, Cincinnati, pp. 43

[6] Rong Shean Lee, Yuh-Min Chen and Chang Zou Lee, (1997), "Development of a concurrent mould design system: a knowledge-based approach", *Computer Integrated Manufacturing Systems*, Vol. 10, No. 4, pp. 287-307

[7] John P. Beaumont, (2006), *Runner and gating design handbook: tools for successful injection moulding* (2nd Edition), ISBN 1-56990-421-3, Hanser, Cincinnati

[8] Brost Enterprises, MOLDQUOTE®, (2007), Technical Specification, http://www.bews.com/index.htm, Accessed 20 March 2010

[9] J. Pauwels, (2002), Magics Tooling Expert ®, Injection moulding 2002 Conference Proceedings, Barcelona, 18-19 March, pp. 279-283

[10] Delcam®, PowerSHAPE-e®, (2010), Technical Specification, http://www.delcam.com, Accessed 20 March 2010

[11] Cimatron®, (2010), CimatronE®, mould quoting module, http://www.cimatron.com/SIP_STORAGE/FILES/0/1760.pdf, Accessed 20 March 2010

[12] QuickParts®, QuickQuote®, (2010), Technical Specification, http://www.quickparts.com, Accessed 20 March 2010

[13] Lawrence J. Lukis, Yuri Arnoldovich Dreizin, John Mark Gilbert, The Protomold Company, Inc., (2004), "Automated quoting of moulds and moulded parts", *United States Patent*, Patent No. US 6,836,699 B2

[14] Lawrence J. Lukis, Christopher Walls-Manning, Mark R. Kubicek, The Protomold Company, Inc., (2006), "Automated multi-customer moulding", *United States Patent*, Patent No. US 7,089,082 B1

[15] Jonathon Fischer, Mold Masters® Limited, (2004), "Method and apparatus for an automated injection moulding configuring and manufacturing system", *United States Patent*, Patent No. US 6,675,055 B1

[16] S. Michikazu, A Hikaru, U. Masayuki, K. Keiichi, H. Hirokatsu, M. Katsuji, Y. Fuminari, W. Masatoshi, S. Noboru, Y. Megumi and S. Daiho, Ricoh® Company Limited, (2008), Injection moulding cost estimation system. *United States Patent*, Patent No. US 7,359,886 B2

[17] Fu Guo, Tadakatsu Yoshikawa, Fujitsu® Limited, (2004), "Mould design system and recording medium", *United States Patent*, Patent No. US 6,546,362 B1.

[18] Claudia Craven, (1999), CadKey® 97 quick reference, ISBN 0-7668-0144-6. Delmar, New York

[19] AutoDesk®, (2010), Autodesk® Inventor® Product Brochure, http://images.autodesk.com/adsk/files/inventor_2011_technical_whats_new_us.pdf, Accessed 20 March 2010

[20] IMSI, (2009), TurboCAD® 16 2D and 3D training guides, IMSI

[21] Siemens® PLM, (2010), UG® NX tooling Brochure, http://www.plm.automation.siemens.com/en_us/Images/4672_tcm1023-4494.pdf, Accessed 20 March 2010

[22] PTC®, (2010), ProEngineer® Tool Design and Expert Mould Base Brochure, http://www.ptc.com/WCMS/files/63763/en/4411_Manufacturing_DS_EN.pdf, Accessed 20 March 2010

[23] Think3®, (2010), Mould Design Datasheet. http://www.think3.com/uploads/6C/M3/6CM3TBSp8q8qg031lyy-Qg/Datasheet_MoldDesign_03_2009_High_en.pdf, Accessed 20 March 2010

[24] VISI®, (2010), VISI® Mould Datasheet. http://www.vero-software.com/cms/files/products/visi/downloads/VISI_Mould.pdf, Accessed 20 March 2010

[25] CAXA®, (2010), CAXA® 2D/3D Datasheet, http://www.caxa.com/cn/zhuanji/caxaenglish/english.html#CAD/CAM, Accessed 20 March 2010

[26] IMOLD®, (2010), IMOLD for Solidworks® Technical Specification, http://www.imold.com/view/page/imold, Accessed 20 March 2010

[27] Dassault systems, (2010), SolidWorks® mechanical CAD capabilities, http://www.solidworks.com/sw/products/mcad-3d-design-software.htm, Accessed 20 March 2010

[28] Dassault systems, (2010), Catia® for mould and die brochure, http://www.plm.automation.siemens.com/en_us/products/velocity/solidedge/overview/add_on_apps/mold_design.shtml, Accessed 20 March 2010

[29] Delcam®, (2010), Delcam® Toolmaker, http://www.powershape.com/general/toolmaker.asp, Accessed 20 March 2010

[30] Siemens® PLM, (2010), Solidedge® mould tooling, http://www.plm.automation.siemens.com/en_us/products/velocity/solidedge/overview/add_on_apps/mold_design.shtml, Accessed 20 March 2010

[31] Cimatron®, (2009), CimatronE® mould design, http://www.cimatron.com/SIP_STORAGE/FILES/0/1760.pdf, Accessed 20 March 2010

[32] Missler Software, (2009), TopSolid® Toolmaking. http://www.plm.automation.siemens.com/en_us/products/velocity/solidedge/overview/add_on_apps/mold_design.shtml, Accessed 20 March 2010.

[33] VX®, (2009), VX® mould and die data sheet. http://www.vx.com/product_data_sheets/VX_MoldDie_datasheet.pdf, Accessed 20 March 2010

[34] PTC, (2009), Co-Create® mould base data sheet, http://www.ptc.com/WCMS/files/71524/en/5193_CoCreate_Moldbase_dh1v2.1.pdf, Accessed 20 March 2010

[35] NTT Data Engineering System Corporation, (2010), Space-E® mould data sheet. http://www.nttd-es.co.jp/english/products/cad/space-e/spe_mold.html, Accessed 20 March 2010

[36] AutoDesk®, (2010), MOLDFLOW® Insight User guide, http://www.moldflow.com, Accessed 20 March 2010

[37] Moldex3D®, (2010), Moldex3D® technical papers, http://www.moldex3d.com, Accessed 20 March 2010

[38] S. Hettinga, (1998), Apparatus for family mould sequential moulding, *United States Patent*, Patent No. 5773038

[39] M. Feick, (2000), Method of injection molding severing a looped gate passage, *United States Patent*, Patent No. 6113828

[40] John P. Beaumont, (2000), Method and apparatus for balancing the filling of injection molds, *United States Patent*, Patent No. 6,077,470

[41] D.W. Rosen, J.R. Dixon and C. Poli, (1992), "Features and algorithms for tooling cost evaluation in injection moulding and die coasting", *Computers in Engineering*, Vol. 1, pp. 1-8

[42] R. Raviwongse and V. Allada, (1997), Artificial neural network based model for computation of injection mould complexity, *International Journal of Advanced Manufacturing Technology*, Vol. 13, pp. 577-586

[43] Adekunle A. Fagade and David O. Kazmer, (2000), “Early Cost Estimation for injection moulded components”, *Journal of Injection Molding Technology*, Vol. 4(3), pp. 97-106

[44] J.R. Dixon and C. Poli, (1995), *Engineering design and design for manufacturing: a structured approach*, ISBN 0964527200, Field Stone Publishers, Conway, Mass

[45] G. Boothroyd, P. Dewhurst, and W. Knight (1994) *Product design for manufacture and assembly*, ISBN 0824791762, Marcel Dekker, New York

[46] E. Shehab and H. Abdalla (2002), “An Intelligent knowledge-Based System for Product Cost Modelling”, *International Journal of Advanced Manufacturing Technology*, Vol. 19, pp. 49-65

[47] O.N. Shing (1999), “Design for manufacture of a cost-based system for moulded parts”, *Advances in Polymer Technology*, Vol. 18(1), pp. 33-42

[48] K.C. Hui and S.T. Tan, (1992), “Mould design with sweep operations. A heuristic approach”, *Computer-Aided Design*, Vol. 24, pp. 81-91

[49] L.L. Chen, S.Y. Chou and T.C. Woo, (1993), “Parting directions for mould and die design”, *Computer-Aided Design*, Vol. 24, pp. 762-768

[50] M. Weinstein and S. Manoochehri, (1996), “Geometric influence of a moulded part on the draw direction range and parting line locations”, *Transactions of ASME Journal of Mechanical Design*, Vol. 118, pp. 29-39

[51] K.C. Hui, (1997), “Geometric aspects of the mouldability of parts”, *Computer-Aided Design*, Vol. 29, pp. 197-208

[52] A.Y.C. Nee, M.W. Fu, J.Y.H. Fuh, K.S. Lee and Y.F. Zhang, (1997), “Determination of optimal parting directions in plastic injection mould design”, *Annals CIRP*, Vol. 46, No. 1, pp. 429-432

[53] M.W. Fu, J.Y.H. Fuh and A.Y.C. Nee, (1999), “ Undercut feature recognition in an injection mould design system”, *Computer-Aided Design*, Vol. 31, pp. 777-790

[54] X.G. Ye, J.Y.H. Fuh and K.S. Lee, (2001), "A hybrid method for recognition of undercut features from moulded parts", *Computer-Aided Design*, Vol. 33, pp. 1023-1034

[55] Rahul Khardekar, G. Burton and S. McMains, (2006), "Finding feasible mould parting directions using graphics hardware", *Computer-Aided Design*, Vol. 38, pp. 327-341

[56] Weigang Hu and Syed Masood (2002), "An Intelligent Cavity Layout Design System for Injection Moulds", *International Journal of CAD/CAM,* Vol. 2, No. 1, pp. 69-75

[57] M.L.H. Low and K.S. Lee, (2003), "A Parametric-controlled cavity layout design system for a plastic injection mould", *International Journal of Advanced Manufacturing Technology,* Vol. 21, pp. 807 - 819

[58] Tatsuya Mochizuki and Naohiro Yuhara, (1991), "Method of determining optimum conceptual layout drawings of cavities in mould design (1st report) – three-plate family moulds", *Journal of Advanced Automation Technology*, Vol. 3, No. 5, pp. 238-243

[59] Irani, R.K. Kim, B.H. and Dixon, J.R., (1995), "Towards automated design of the feed system of injection moulds by integrating CAE, iterative redesign and features", *Transactions ASME Journal Engineering for Industry*, Vol. 117, No. 1, pp. 72-77

[60] Y.C. Lam and L.W. Seow, (2000), "Cavity balance for plastic injection moulding", *Polymer Engineering Science*, Vol. 406, pp. 1273-1280

[61] Y.C. Lam and S. Jin, (2001), "Optimisation of gate location for plastic injection moulding", *Journal of Advanced Automation Technology*, Vol. 5, No. 3, pp. 180-192

[62] F. Shi, Z.L. Lou, J.G. Lu and Y.Q. Zhang, (2003), " An improved Rough Set Approach to Design of Gating Scheme for Injection Moulding", *International Journal of Advanced Manufacturing Technology*, Vol. 21, pp. 662-668

[63] M. Zhai and C, Shen, (2004), "Algorithm to optimise number of gates and locations in an injection mould", *Plastics, Rubbers and Composites*, Vol. 33, No. 8, pp. 330-334

[64] Y.C. Lam, G.A. Britton and D.S. Liu, (2004), "Optimisation of gate location with design constraints", *International Journal of Advanced Manufacturing Technology*, Vol. 24, pp. 560-566

[65] K.S. Lee and J.C. Lin, (2006), "Design of the runner and gating system parameters for a multi-cavity injection mould using FEM and neural network", *International Journal of Advanced Manufacturing Technology,* Vol. 27, pp. 1089-1096

[66] R.K. Irani, S. Kodiyalam and D.O. Kazmer, (1992), "Runner system balancing for injection moulds using approximation concepts and numerical optimization", *Proceedings of 18th Annual ASME Design Automation Conference*, Montreal, September, pp. 255-261

[67] B.H. Lee and B.H. Kim, (1996), "Automatic design for the runner system of injection moulds based on packing simulation", *Polymer Plastics Technology Engineering*, Vol. 25, No.1, pp. 147-168

[68] K.C. Chen, R.Y. Chang, David C. Hsu, Alice S. Lin and Kelly Lu, (2000), "A fast approach to automatic runner balance", *ANTEC 2000: Conference Proceeding*, Vol. 1, pp.609-611

[69] Kevin Alam and Musa R. Kamal, (2004), "Runner balancing by a direct genetic optimisation of shrinkage", *Polymer Engineering Science*, Vol. 44, No. 10, pp.1949-1959

[70] Kevin Alam and Musa R. Kamal, (2005), "A robust optimisation of injection moulding runner balancing", *Computer in Chemistry Engineering*, Vol. 29, pp.1934-1944

[71] M. Zhai, Y.C. Lam and C.K. Au, (2009), "Runner sizing in multiple cavity injection mould by non-dominated sorting genetic algorithm", *Engineering with Computer*, Vol. 25, No.3, pp. 237-245

[72] C.K. Au, (2005), "A geometric approach for injection mould filling simulation", *International Journal of Machine Tools and Manufacturing*, Vol. 45, pp. 115-124

[73] Q. Zou, (1992), "Injection moulding cooling optimization", *ANTEC '92*, pp. 1614–1620

[74] L.Q. Tang, K. Pochiraju, C. Chassapis and S. Manoochehri, (1998), "A computer-aided optimisation approach for the design of injection mould cooling systems", *Tanscation of ASME Journal of Mechanical Design*, Vol. 120, pp. 165-174

[75] S.J. Park and T.H. Kwon, (1998), "Optimal cooling system design for the injection moulding process", *Polymer Engineering and Science*, Vol. 389, No. 9, pp. 1450-1462

[76] E. Sachs, E. Wylonis, S. Allen, M. Cima and H. Guo, (2000), "Production of injection moulding tooling with conformal cooling channels using the three dimensional printing process", *Polymer Engineering and Science,* Vol. 40, No. 5, pp. 1232-1247

[77] X. Xu, E. Sachs and S. Allen, (2001), "The design of conformal cooling channels in injection moulding tooling", *Polymer Engineering and Science,* Vol. 41, No. 7, pp. 1265-1279

[78] Y.F. Sun, K.S. Lee and A.Y.C. Nee, (2002), "The application of U-shape milled grooves for cooling of injection moulds", *Journal of Engineering Manufacture, Proceedings of the IMechE, Part B*, Vol. 216, pp. 1561-1573

[79] Y.F. Sun, K.S. Lee and A.Y.C. Nee, (2004), "Design and FEM analysis of the milled groove insert method for cooling of plastic injection moulds", *International Journal of Advanced Manufacturing Technology,* Vol. 24, pp. 715-726

[80] K.M. Au and K.M. Yu, (2007), "A scaffolding architecture for conformal cooling design in rapid plastic injection moulding", *International Journal of Advanced Manufacturing Technology,* Vol. 34, pp. 496-515

[81] Y.S. Ma and T. Tong, (2004), "An object-oriented design tool for associative cooling channels in plastic injection moulds", *International Journal of Advanced Manufacturing Technology,* Vol. 23, pp. 79-86

[82] C.L. Li, (2001), "A feature-based approach to injection mould cooling system design", *Computer-Aided Design*, Vol. 33, pp. 1073-1090

[83] C.L. Li, C.G. Li and A.C.K. Mok, (2005), "Automatic layout design of plastic injection mould cooling system", *Computer-Aided Design*, Vol. 37, pp. 645-662

[84] C.L. Li, (2007), "Part segmentation by superquadric fitting - a new approach towards automatic design of cooling system for plastic injection mould", *International Journal of Advanced Manufacturing Technology,* Vol. 35, pp. 102-114

[85] C.G. Li and C.L. Li, (2007), "An evolutionary approach to the automatic layout design of plastic injection mould cooling system", ICMA2007, Singapore, May 2007, pp. 25-28

[86] Z. Wang, K.S. Lee, J.Y.H. Fuh, Z. Li, Y.F. Zhang, A.Y.C. Nee and D.C.H. Yang, (1996), "Optimum ejector system design for plastic injection mould", *International Journal of Materials and Product Technology*, Vol. 11, No. 5/6, pp. 371-385

[87] S. Kawk, T. Kim, S. Park and K. Lee, (2003), "Layout and sizing of ejector pins for injection mould design using the wavelet transform", *Proceedings of the Institution of Mechanical Engineers*, Vol. 217, Part B, pp. 463-473

[88] David Anthony Cinquegrana., (1990), "Knowledge-based injection mould design automation", D.Eng. Thesis, Department of Plastic Engineering, University of Massachusetts Lowell

[89] C.K. Mok, K.S. Chin and J.K.L. Ho, (2001), "An interactive knowledge-based CAD system for mould design in injection moulding processes", *International Journal of Advanced Manufacturing Technology*, Vol. 17, pp. 27-38

[90] X.G. Ye, Y.H. Fuh and K.S. Lee, (2000), "Automated assembly modelling for

plastic injection moulds", *International Journal of Advanced Manufacturing Technology*, Vol. 16, pp. 739-747

[91] T.L. Neo and K.S. Lee, (2001), "Three-Dimensional kernel development for injection mould design", *International Journal of Advanced Manufacturing Technology*, Vol. 17, pp. 453-461

[92] Y.S. Ma, S.B. Tor and G.A. Britton, (2003), "The development of a standard component library for plastic injection mould design using an object-oriented approach", *International Journal of Advanced Manufacturing Technology*, Vol. 22, pp. 611-618

[93] W.M. Chan, L. Yan, W. Xiang and B.T. Cheok, (2003), "A 3D CAD knowledge-based assisted injection mould design system", *International Journal of Advanced Manufacturing Technology*, Vol. 22, pp. 387-395

[94] Tatsuya Mochizuki and Naohiro Yuhara, (1990), "Decision support system for making mould specifications", *Proceedings of the 1990 Japan-U.S.A. symposium on flexible automation*, pp. 1227 - 1232

[95] Jagannath Yammada, Terrence L. Chambers and Suren N. Dwivedi, (2002), "Intelligent tool for plastic injection mould design", *Advances in concurrent engineering: proceedings of the 9th ISPE international conference on concurrent engineering,* pp. 569-574

[96] S.Q. Xie, P.L. Tu and Z.D. Zhou, (2004), "Internet-based DFX for rapid and economical tool/mould making", *International Journal of Advanced Manufacturing Technology*, Vol. 24, pp. 821-829

[97] H.B. Qiu and C.X. Li, (2004), "Conceptual design support system in a collaborative environment for injection moulding", *International Journal of Advanced Manufacturing Technology*, Vol. 24, pp. 9-15

[98] W.R. Jong, C.H. Wu, H.H. Liu and M.Y. Li, (2009), "A collaborative navigation system for concurrent mould design", *International Journal of Advanced Manufacturing Technology*, Vol. 40, pp. 215-225

[99] X.G. Ye, K.S. Lee, J.Y.H. Fuh and Y.F. Zhang, (2001), "Automatic initial

design of injection mould“, *International Journal of Materials and Product Technology*, Vol. 16, No. 6/7, pp. 592-604

[100] G. Pahl and W. Beitz, (1996), *Engineering design – a systematic approach,* (2nd Edition), ISBN: 3540199179, Springer, London

[101] Martyn Denscombe, (2007), *The good research guide for small-scale social research projects,* (3rd Edition), ISBN: 0035220223, McGraw-Hill Open University Press, London

[102] Carolyn B. Seaman, (1999), "Qualitative methods in empirical studies of software engineering", *IEEE Transactions on Software Engineering*, Vol. 25, No. 4, pp. 1-16

[103] Forrest Shull, Janice Singer and Dag I.K. Sjøberg, (2008), *Guide to advanced empirical software engineering*, ISBN: 978-1-84800-043-8, Springer, London

[104] Danny L. Jorgensen, (1989), *Participant observation: a methodology for human studies*, ISBN: 0803928769, SAGE, London

[105] R.K. Yin, (2002), *Case study research: design and methods*, ISBN: 1412960991, SAGE, London

[106] Tim Rapley, (2007), *Doing conversation, discourse and document analysis*, ISBN: 9780761949817, SAGA, London

[107] Tony Buzan, (2000), *The mind map book*, ISBN: 0452273226, Penguin Books, New York

[108] G.C. Onwubolu, (2004), *New optimisation techniques in engineering*, ISBN: 354020167X, Springer, Berlin

[109] S. Sumathi, T. Hamsapriya and P. Surekha, (2008), *Evolutionary intelligence: an introduction to theory and applications with Mathlab*, ISBN: 978-3-540-75158-8, Springer, Berlin

[110] S.S. Rao, (2009), *Engineering optimisation: theory and practice (4th Edition)*, ISBN: 978-0-470-18352-6, Wiley, Hoboken, New Jersey

[111] J.E. Baseley, (1985), "An exact two-dimensional non-guillotine cutting tree search procedure", *Operational Research*, Vol. 33, pp. 49-65

[112] Yaodong Cui, Yuli Yang, Xian Cheng, Peihua Song, (2006), "A recursive branch-and-bound algorithm for the rectangular guillotine strip packing problem", *Computers & Operations Research*, Vol. 35, pp. 1281-1291

[113] M.D. Landon and R.J. Balling, (1994), "Optimal packaging of complex parametric solids according to mass property criteria", *Journal of Mechanical Design*, Vol. 116, pp. 375-381

[114] Kathryn A. Dowsland and William B. Dowsland, (1992), "Packing problems", *European Journal of Operational Research*, Vol. 56, pp. 2-14

[115] Andrea Lodi, Silvano Martello and Michele Monaci, (2002), "Two-dimensional packing problems: A survey", *European Journal of Operational Research*, Vol. 141, pp. 241-252

[116] J. Cagan, K. Shimada and S. Yin, (2002), "A survey of computational approaches to three-dimensional layout problems", *Computer-Aided Design*, Vol. 34, pp. 597-611

[117] Fred Glover, (1989), "Tabu search – part I", *ORSA Journal on Computing*, Vol. 1, No. 3, pp 190-206

[118] Fred Glover, (1989), "Tabu search – part II", *ORSA Journal on Computing*, Vol. 2, No. 1, pp 4-32

[119] Fred Glover and Manuel Laguna, (1997), *Tabu search*, ISBN: 079239965X, Kluwer academic publishers, Boston

[120] J. Blazewicz, P. Hawryluk and R. Walkowiak, (1993), "Using a tabu search approach for solving the two-dimensional irregular cutting problem", *ANNALS of operation research*, Vol. 41, No. 4, pp. 313-325

[121] R. Alvarez-Valdes, F. Parreno and J. M. Tamarit, (2005), "A tabu search algorithm for a two-dimensional non-guillotine cutting problem", *European Journal of Operational Research*, Vol. 183, pp. 1167-1182

[122] G.T. Crainic, G. Perboli and R. Tabei, (2009), “A two-level tabu search for the three-dimensional bin-packing problem”, *European Journal of Operational Research*, Vol. 195, No. 3, pp. 744-760

[123] S. Kirkpatrick, C. D. Jr. Celatt and M.P. Vecchi, (1983), “Optimisation by simulated annealing”, *Science*, Vol. 220, No. 4598, pp. 671-679

[124] R. A. Rutenbar, (1989), “Simulated annealing algorithms: an overview”, *IEEE Circuits and Devices Magazine*, Vol. 5, No. 1, pp. 19-26

[125] C. Sechen, (1988), *VLSI placement and global routing using simulated annealing*, ISBN: 0898382815, Kluwer Academic publishers, M.A., Boston

[126] D.F. Wong, H.W. Leong and C.L. Liu, (1988), *Simulated annealing for VLSI design*, ISBN: 0898382564, Kluwer Academic publishers, M.A., Boston

[127] T.Y. Wang, K.B. Wu, Y.W. Liu, (2001), “A simulated annealing algorithm for facility layout problems under variable demand in Cellular Manufacturing Systems”, *Computers in Industry*, Vol. 46, No. 2, pp. 181-188

[128] S. Szykman and J. Cagan, (1995), “A simulated annealing approach to three-dimensional component packing”, *ASME Journal of Mechanical Design*, Vol. 117, No. 2A, pp. 308-314

[129] S. Szykman, J. Cagan and P. Weisser, (1998), “An integrated approach to optimal three dimensional layout and routing”, *ASME Journal of Mechanical Design*, Vol. 120, No. 3, pp. 510-512

[130] E. Burke and G. Kendall, (1999), “Applying simulated annealing and the no fit polygon to the nesting problem”, *In proceedings of the world manufacturing congress*, 27-30, Durham, UK

[131] John H. Holland, (1973), ”Genetic Algorithms and the optimal allocations of trials”, *SIAM Journal of Computing*, Vol. 2, No. 2, pp. 88-105

[132] Francis E.H. Tay, T. Y. Chong and F.C. Lee, (2002), “Pattern nesting on irregular-shaped stock using genetic algorithms”, *Engineering Applications of Artificial Intelligence*, Vol. 15, pp. 551-558

[133] Leo H.W. Yeung and Wallace K.S. Tang, (2004), "Strip-packing using hybrid genetic approach", *Engineering Applications of Artificial Intelligence*, Vol. 17, pp. 169-177

[134] Andreas Bortfeldt, (2006), "A genetic algorithm for the two-dimensional strip packing problem with rectangular pieces", *European Journal of Operational Research*, Vol. 172, pp. 814-837

[135] Eleni Hadjiconstantinou and Manuel Iori, (2007), "A hybrid genetic algorithm for the two-dimensional single large object placement problem", *European Journal of Operational Research*, Vol. 183, pp. 1150-1166

[136] José Fernando Gonçalves, (2007), "A hybrid genetic algorithm-heuristic for a two-dimensional orthogonal packing problem", *European Journal of Operational Research*, Vol. 183, pp. 1212-1229

[137] A. Soke and Z. Bingui, (2006), "Hybrid genetic algorithm and simulated annealing for two-dimensional non-guillotine rectangular packing problems", *Engineering Applications of Artificial Intelligence*, Vol. 19, pp.557-567

[138] S. Koakutsu, Y. Sugai and H. Hirata, (1992), "Floorplanning by improved simulated annealing based on genetic algorithm", *IEE Trans Inst Electr Eng Jpn*, Vol. 112(C-7), pp. 411-416

[139] V. Schnecke and O. Vornberger, (1995), "Genetic Design of VLSI Layouts", *Proceedings of GALESIA'95*, Sheffield, pp. 430-435

[140] P. Mazumder and E.M. Rudnick, (1999), *Genetic algorithms for VLSI design, layout and test automation*, ISBN 0-13-011566-5, Prentice, Upper Saddle River, NJ

[141] Basheer M. Khumawala, Marvin A. Arostegui Jr. and Sukran N. Kadipasaoglu, (2006), "An empirical comparison of tabu search, simulated annealing, and genetic algorithms for facilities location problems", *International Journal of Production Economics*, Vol. 103, pp. 742-754

[142] S.P. Singh and R.R.K. Sharma, (2006), "A review of different approaches to the facility layout problems", *International Journal of Advanced*

Manufacturing Technology, Vol. 30, pp. 425-433

[143] M. Adamowicz and A. Albano, (1976), “Nesting two-dimensional shapes in rectangular modules”, *Computer-Aided Design*, Vol. 8, pp. 27-33

[144] J. A. George and D. F. Robinson, (1980), “A heuristic for packing boxes into a container”, *Computers and Operational Research*, Vol. 7, pp. 147-156

[145] S. Israni and J.L. Sanders, (1985), “Performance testing of rectangular parts-nesting heuristics”, *International Journal of Production Research*, Vol. 23, pp. 437-456

[146] A. Miguel Gomes and Jose F. Oliveira, (2002), “A 2-exchange heuristic for nesting problems”, *European Journal of Operational Research*, Vol. 141, pp. 359-370

[147] Kathryn A. Dowsland, Subodh Vaid and William B. Dowsland, (2002), “An algorithm for polygon placement using a bottom-left strategy”, *European Journal of Operational Research*, Vol. 141, pp. 371-381

[148] S.M.A. Suliman, (2006), “A sequential heuristic procedure for the two-dimensional cutting-stock problem”, *International Journal of Production Economics*, Vol. 99, pp. 177-185

[149] E.Y. Kalay, (2004),”Architecture’s New Media. Principles, Theories, and Methods of Computer-Aided Design”, ISBN: 0-262-11284-1, MIT Press, Cambridge, Massachusetts, pp. 223-293

[150] R.S. Frew, (1980), “A survey of space allocation algorithms in use in architectural design in the past twenty years”, *Proceedings of the 17th conference of design automation*, Minneapolis, Minnesota, United States, pp 165-174

[151] S.A. Arvin and D.H. House, (1999), “Modelling architectural design objectives in physically based space planning”, *ACADIA*, pp. 212-225

[152] G. Stiny and J. Gips, (1972), “Shape Grammars and the generative specification of painting and sculpture”, *Proceedings of IFIP Congress 71*,

Amsterdam, North Holland, pp. 1460-1465

[153] G, Stiny and W.J. Mitchell, (1978), "The Palladian grammar", *Environment and Planning*, Vol. B5, No. 17

[154] H. Koning and J. Eisenberg, {1981}, "The language of the prairie: Feank Lioyd Wright's prairie houses", *Building and Environment*, Vol. B8, pp. 295-323

[155] U. Flemming, (1987), "More than the sum of its parts: the grammar of Queen Anne houses", *Building and Environment*, Vol. B14, pp. 323-350

[156] G. Stiny, (1980), "Kindergarten grammars: designing with Froebel's building gifts", *Environment and Planning*, Vol. B3, pp. 409-462

[157] T.W. Knight, (1992), "Designing with grammars", *CAAD Futures 91 Conference Proceedings*, Zurich, Switzerland, pp. 33-48

[158] T.W. Knight, (1981), "Languages of designs: from known to new", *Environment and Planning*, Vol. B8, pp. 213-238

[159] T.W. Knight, (1983), "Transformations of languages of designs", *Environment and Planning*, Vol. B10, Part 1, pp. 125-128

[160] T.W. Knight, (1994), *Transformations in design: a formal approach to change and innovation in the visual arts*, ISBN 0521384605, Cambridge University Press, Cambridge

[161] Francois Grobler, Aila Aksamija and Hyunjoo Kim, (2008), "Ontologies and shape grammars: communication between knowledge-based and generative systems", *Design Computing and Cognition '08*, pp. 23-40

[162] M.A. Rosenman (1996), "The generation of form using an evolutionary approach", *Artificial Intelligence '96* (J. S. Gero and F. Sudweeks eds.), ISBN: 0-7923-4040-9, Kluwer Academic, Dordrecht, The Netherlands, pp. 643 – 662

[163] Orestea Chouchoulas, (2003), "Shape evolution: an algorithmic method for conceptual architectural design combining shape grammars and genetic

algorithms", Ph.D. Thesis, Department of Architecture and Civil Engineering, University of Bath

[164] P.J. Bentley and J.P. Wakefield, (1996), "The Evolution of Solid Object Designs using Genetic Algorithms", *Modern Heuristic Search Methods* (Rayward-Smith, V. eds.), Ch. 12, John Wiley & Sons Inc., pp. 199-215

[165] P. J. Bentley and J.P. Wakefield, (1996), "Conceptual Evolutionary Design by Genetic Algorithms", *Engineering Design and Automation Journal*, Vol. 2:3, John Wiley & Sons Inc

[166] P. J. Bentley and J.P. Wakefield, (1998), "Generic Evolutionary Design", *Soft Computing in Engineering Design and Manufacturing* (P.K. Chawdhry, R. Roy, and R.K. Pank eds.), ISBN: 978-3-540-76214-0, Springer, London, Part 6, pp. 289-298

[167] Gabor Renner and A. Ekart, (2003), "Genetic algorithms in computer aided design", *Computer-Aided Design*, Vol. 35, pp. 709-726

[168] P.J. Bentley, (1999), *Evolutionary design by computers*, ISBN: 1-1558-60605-X, Morgan Kaufmann, California

[169] R.F. Woodbury, (1993), *A genetic approach to creative design", Modelling Creativity and Knowledge-Based Creative Design* (J. S. Gero and M. L. Maher, eds.), ISBN: 0-80581-153-2, Lawrence Erlbaum, Hillsdale, New Jersey, pp. 211-232

[170] Anthony J.F. Griffiths, Susan R. Wessler, Richard C. Lewontin and Sean B. Carroll, (2008), *Introduction to genetic analysis*, (9th edition), ISBN 0716749394, W. H. Freeman, New York

[171] R.G. Gillespie and, G.S. Oxford, (1998), "Selection on the colour polymorphism in Hawaiian happy-face spiders: evidence from genetic structure and temporal fluctuations", *Evolution*, Vol. 52, pp. 775-783

[172] J.S. Gero and V. Kazakov, (1998), "Evolving design genes in space layout problems", *Artificial Intelligence in Engineering*, Vol. 12, No. 3, pp. 163-176

[173] Emanuel Falkenauer, (1998), *Genetic Algorithms and Grouping Problems*, ISBN: 0-471-97150-2, John Wiley & Sons, Chichester, England

[174] PTC®, (2010), Pro/Engineer® Pro/Toolkit API Wizard, "<proe_loadpoint>/protoolkit/protkdoc/tkuse.pdf", Accessed 20 March 2011

[175] J.T. Alander, (1992), "On optimal population size of genetic algorithms", *CompEuro 1992 Proceedings, Computer systems and software engineering, 6th Annual European Computer Conference*, Hague, 4-8 May 1992, pp. 65-70

[176] K.A. DeJong, (1975), "An analysis of the behaviour of a class of genetic adaptive systems", Ph.D. Thesis, Department of Computer and Communication Sciences, University of Michigan

[177] John H. Holland, (1975), *Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence*, ISBN: 0-262-58111-6, The MIT press, Cambridge, Massachusetts

[178] David E. Goldberg, Kalyanmoy Deb and James H. Clark, (1992), "Genetic algorithms, noise, and the sizing of populations", *Complex Systems*, Vol. 6, pp. 333-362

[179] T. Back, (1991), "Self adaptation in genetic algorithms", *Towards a practice on Autonomous systems*, ISBN: 0-262-72019-1, The MIT press, Cambridge, Massachusetts, pp. 263-271

[180] T. Back, (1992), "The interaction of mutation rate, selection, and self-adaptation within a genetic algorithm", *Parallel Problem Solving from nature 2*, Brussels, Belgium, 28-30 September 1992, Elsevier, pp. 85-94

[181] Jim Smith and Terence C. Fogarty, (1996), "Self adaptation of mutation rates in a steady state genetic algorithm", *International Conference on Evolutionary Computation (1996)*, pp. 318-323

[182] Zanshan Ma, (2009), "Towards a population dynamics theory for evolutionary computing: learning from biological population dynamics in nature", *AICI 2001*, LNAI 5855, pp. 195-205

[183] Khadiza Tehera, Raafat N. Ibrahim and Paul B. Lochert, (2008), "GADYM – a novel genetic algorithm in mechanical design problems", *Journal of Universal Computer Science*, vol. 14, no. 15, pp. 2566-2581

[184] Sensable® Technology Incorporation, (2010), "FreeForm® modelling version 11 - A guide to what's new in this release", http://www.sensable.com/documents/documents/v11_WhatsNew.pdf, Accessed 20 June 2011, pp. 22-25

[185] David O. Kazmer, Mark D. Moss and Mark Doyle, Synventive® Molding Solutions, Inc., (2003), "Dynamic feed control system", *United States Patent*, Patent No. US 6,632,079 B1

[186] M. Doyle, A. Bernier, K. Camile and David O. Kazmer, (1995), "Utilisation of dynamic feed control in family tools", *ANTEC*, Indianapolis, 1995

[187] Jim F. Reilly, M. Doyle and David O. Kazmer, (2001), "An assessment of dynamic feed control in modular tooling", *The Journal of Injection Moulding Technology*, Vol. 5, No. 1, pp. 49-60

[188] T/Mould Solution GmbH & Co.KG, (2011), TandemMoulds, http://www.tandemmould.com/en/tandemtechnique.html, Accessed 20 March 2011

APPENDIX A – Summary of formulations for cost evaluation

A.1 Cost of mould insert (C_n)

$$\boxed{C_{n,i} = X_i * Y_i * Z_i * D_n * P_n} \tag{A.1}$$

where $C_{n,i}$ is the estimated cost of the mould insert for design solution (i) (HK$),

X_i is the horizontal dimension of the mould base for design solution (i) (mm),

Y_i is the vertical dimension of the mould base for design solution (i) (mm),

Z_i is the total height of the mould base (mm),

D_n is the density of the material of the mould base (kg / mm^3),

P_n is the price of the material of the mould base (HK$ / kg).

A.2 Cost of mould base (C_m)

$$\boxed{C_{m,i} = 0.9*(5*W_i + W_i*L_i*H_i*D_m*P_m)} \qquad \textbf{(A.2)}$$

where $C_{m,\,i}$ is the estimated cost of the mould base of design solution (i) (HK$),

W_i is the horizontal dimension of the mould base of design solution (i) (mm),

L_i is the vertical dimension of the mould base of design solution (i) (mm),

H_i is the total height of the mould base of design solution (i) (mm),

D_m is the density of the material of the mould base (Kg / mm^3),

P_m is the price of the material of the mould base (HK$ / Kg)

A.3 Cost of runners (C_r)

$$V_{total,i} = \sum_{j=1}^{m} N_{i,j} * V_{i,j} = \sum_{j=1}^{m} N_{i,j} * L_{i,j} * (\pi r_{i,j}^{2}) \quad \textbf{(A.3.1)}$$

where *m* is the number of different types of segments in the runner system of design solution (i),

j is an index referring to a specific runner segment of design solution (i),

$N_{i,j}$ is the number of the runner segment j of design solution (i),

$V_{i,j}$ is the volume of the runner segment j of design solution (i),

$L_{i,j}$ is the length of the runner segment j of design solution (i) (mm),

$r_{i,j}$ is the radius of the runner segment j of design solution (i) (mm).

$$C_{r,i} = V_{total,i} * D_r * P_r * S \quad \textbf{(A.3.2)}$$

where $C_{r,i}$ is the estimated cost of runner of design solution (i) (HK\$),

D_r is the density of the plastic material (g/mm^3),

P_r is the price of the plastic material (HK\$/g),

S is the total number of shots required for the whole production

A.4 Cost of external sliders (C_s)

$$C_{s,i} = \overbrace{K_1T_i}^{\text{Fixed assembly cost}} + \overbrace{K_2T_i}^{\text{Fixed machining cost}} + \sum_{j=1}^{T_i} (\overbrace{K_3V_{i,j}}^{\text{Variable material cost}} + \overbrace{K_4V_{i,j}}^{\text{Variable machining cost}}) \qquad \text{(A.4)}$$

where i is an index referring to design solution (i),

j is an index referring to the individual slider used for design solution (i),

T_i is the total number of sliders used for design solution (i),

K_1 is the coefficient of the fixed assembly cost = 600 (HK$/slider),

K_2 is the coefficient of the fixed machining cost = 600 (HK$/slider),

K_3 is the coefficient of the variable material cost = 0.003 (HK$/mm^3),

K_4 is the coefficient of the variable machining cost = 0.005 (HK$/mm^3),

$V_{i,j}$ is the envelope size (L x B x D) of individual slider assembly j used for design solution (i) (mm^3)

A.5 Cost of injection moulding (C_j)

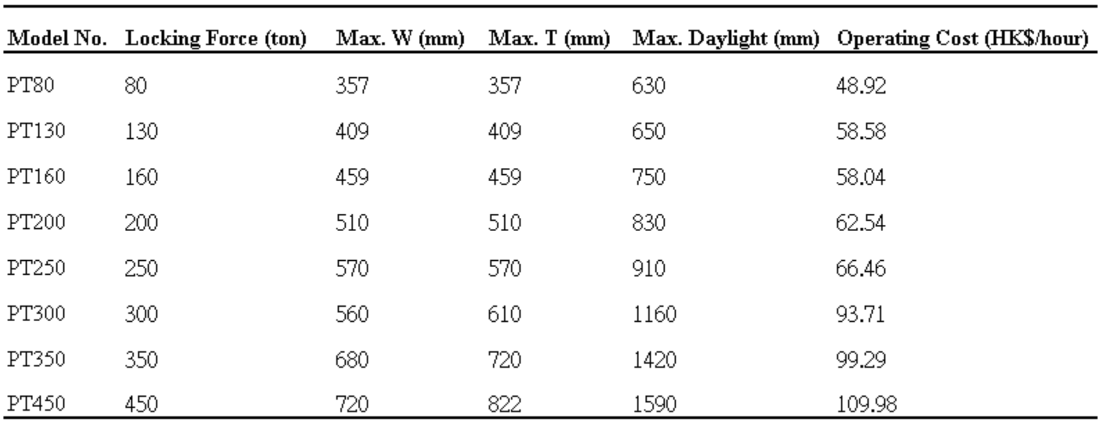
$$\boxed{C_{j,\,i} = S(t/3600)P_i} \qquad \textbf{(A.5)}$$

where i is an index referring to design solution (i),

S is the total number of shots required for the whole production,

t is the estimated cycle time per shot (seconds),

P_i[1] is the average operating cost of the required injection moulding machine for design solution (i) (HK$/hour)



Model No.	Locking Force (ton)	Max. W (mm)	Max. T (mm)	Max. Daylight (mm)	Operating Cost (HK$/hour)
PT80	80	357	357	630	48.92
PT130	130	409	409	650	58.58
PT160	160	459	459	750	58.04
PT200	200	510	510	830	62.54
PT250	250	570	570	910	66.46
PT300	300	560	610	1160	93.71
PT350	350	680	720	1420	99.29
PT450	450	720	822	1590	109.98

Table A.5.1. The technical parameters and the average operation cost of the injection moulding machines in Luen Shing Tools Limited (Courtesy: Luen Shing Tools Limited)

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[1] *The maximum space between tie bars, the maximum daylight and the operating cost of all available injection moulding machines in Luen Shing Tools limited are listed in Table A.5.1*

APPENDIX B - Summary of formulations for performance evaluation

B.1 Flow path balance performance (P_f)

$$\text{Flow Path Balance Ratio (FPBR)} = \frac{\sum_{i=1}^{n} (FP_i / FP_{min}) - 1}{n - 1} \tag{B.1.1}$$

where i is the index number of individual cavity,

n is the total number of cavities in the family mould,

FP_i is the flow path length measured from the starting point of the sprue to the boundary of the cavity (mm),

FP_{min} is the minimum flow path length among all flow path lengths (mm)

$$\text{Flow Path Balance Performance } (P_f) = \frac{FPBR_{goal}}{FPBR_i} * 100\% \tag{B.1.2}$$

where $FPBR_{goal}$ is the user-defined goal FPBR value (ideally equal to 1),

$FPBR_i$ is the FPBR value of design solution (i).

B.2 Runner diameter balance performance (P_r)

$$\text{Runner Diameter Balance Ratio (RDBR) at junction } (J_{i,j}) = \frac{R_{max} \text{ at junction } (J_{i,j})}{R_{min} \text{ at junction } (J_{i,j})} \quad \textbf{(B.2.1)}$$

where R_{max} is the maximum runner diameter (mm) at junction ($J_{i,j}$) excluding the input runner,

R_{min} is the minimum runner diameter (mm) at junction ($J_{i,j}$) excluding the input runner,

i is an index referring to Design solution (i),

j is an index referring to Junction (j) of Design solution (i)

$$RDBR_i = \max\left\{RDBR_{i,1}, RDBR_{i,2} \ldots\ldots RDBR_{i,n}\right\} \quad \textbf{(B.2.2)}$$

where $RDBR_i$ is the maximum value across all RDBR at junction ($J_{i,j}$),

i is an index referring to Design solution (i),,

j is an index referring to Junction (j) of Design solution (i),

n is the total number of junctions in the runner system of Design solution (i)

$$\text{Runner Diameter Balance Performance } (P_r) = \frac{RDBR_{goal}}{RDBR_i} * 100\% \tag{B.2.3}$$

where RDBR$_{goal}$ is the user-defined goal RDBR value (usually equal to 1.2),

RDBR$_i$ is the RDBR value of design solution (i).

B.3 Clamping force balance performance (P_c)

$$X_c = \frac{\sum_{i=1}^{n}(F_i * X_i)}{\sum_{i=1}^{n} F_i} \qquad \text{(B.3.1)}$$

$$Y_c = \frac{\sum_{i=1}^{n}(F_i * Y_i)}{\sum_{i=1}^{n} F_i} \qquad \text{(B.3.2)}$$

where X_c is the X-coordinate of the centre of the resultant clamping force measured from the centre of the family mould,

Y_c is the Y-coordinate the centre of the resultant clamping force measured from the centre of the family mould,

i is the index of individual part in the family mould,

n is the total number of parts in the family mould,

F_i is the estimated clamping force for the part (i),

X_i is the X-coordinate of the centre of the estimated clamping force acting on the part (i) measured from the centre of the family mould,

Y_i is the Y-coordinate of the centre of the estimated clamping force acting on the part (i) measured from the centre of the family mould,

$$\mathbf{d} = \sqrt{(X_c)^2 + (Y_c)^2} \qquad \textbf{(B.3.3)}$$

$$\textbf{Clamping force balance performance } (P_c) = \frac{d_{goal}}{d_i} * 100\% \qquad \textbf{(B.3.4)}$$

where d_{goal} is the pre-defined goal value of the offset distance of the centre of the resultant clamping,

d_i is the offset distance of the individual design solution (i)

B.4 Drop time performance (P_d)

$$t_i = \sqrt{2h_i/a} \qquad \textbf{(B.4.1)}$$

where t_i (second) is the time of free fall for the design solution (i),

h_i (m) is the falling distance required to clear the moulding area before re-closing the mould,

a is the gravity (m/s^2)

$$\text{Drop time performance } (P_d) = \frac{t_{goal}}{t_i} * 100\% \qquad \textbf{(B.4.2)}$$

where t_{goal} is the pre-defined goal value of the drop time,

t_i is the estimated drop time of Design solution (i)

APPENDIX C - The Algorithm for the generation of an initial population

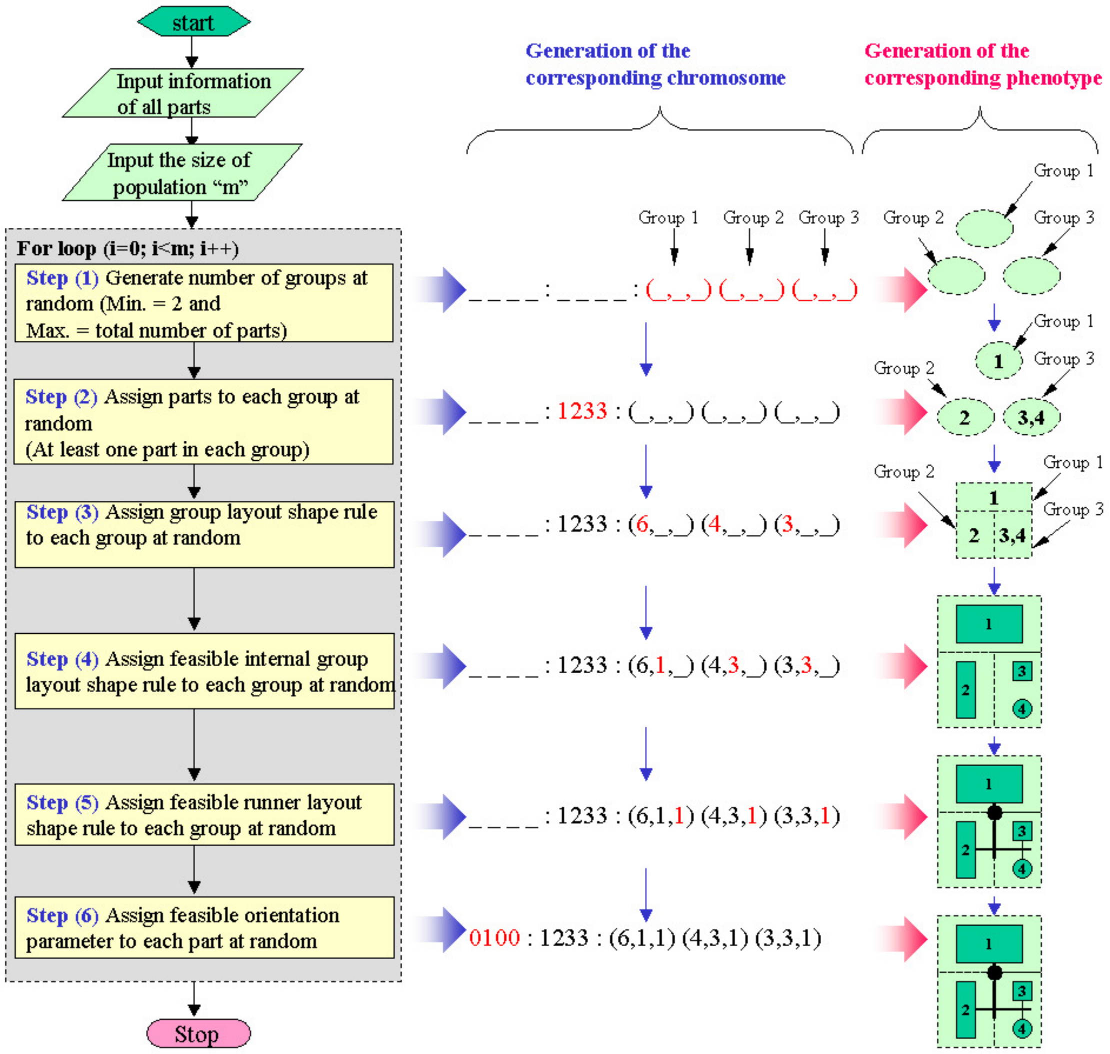

Figure C.1. The proposed algorithm to generate chromosomes for the initial population

Figure C.1 shows the algorithm flow diagram and the step-by-step chromosome generation process. First of all, the information of the moulding parts must be input by the mould designers. The information includes part shape (circular or irregular), overall part size, part weight, type of gate, gate location, number of sliders and so forth. The population size 'm' must be specified before the recursive loop, starting from steps 1 to 6, begins. The loop will be stopped when the number of generated individual design solutions is equal to the specified population size 'm'. Step (1) is to generate a number of groups at random. The minimum number of moulding parts 'n' must be equal to or more than two. The virtual multi-cavity group must contain at least one part. Therefore, the minimum number of groups must be equal to two and the maximum number of groups must be equal to the number of moulding parts 'n' in a family mould. The number of virtual multi-cavity groups can be selected at random within the range (2 to n). Step (2) is to assign parts to each group at random. For example, Part 1 and Part 2 are assigned to Group 1 and Group 2 respectively. Parts 3 and 4 are assigned to Group 3. Then, the group session of the chromosome becomes '1233'. The graphical representation of its phenotype is shown on the left-hand side of Figure C.1. Step (3) is to assign a group layout shape placement rule to each group at random. The rule identification number is selected for each group at random from the list of group layout shape placement rules (1-12) as defined in Section 4.3.1. Step (4) is to assign a feasible internal group layout shape rule to each group at random. The rule identification number is selected for each group at random from the valid list of internal group layout shape rules (1-7) as defined in Section 4.3.1. Subsequently, Step (5) is to assign feasible runner layout shape rules to each group at random. Based on the number of parts in the virtual multi-cavity group and the internal cavity group layout shape rules, a rule identification number is selected at random from the valid list of runner layout shape rules (1-4) as defined in Section 4.3.1. Finally, Step (6) is to assign a feasible orientation parameter to each part at random. The feasible orientation parameter of each cavity is selected at random depending on the existing group layout, internal group cavity layout and runner layout.

APPENDIX D - Summary of formulations of runner sizing and slider design rules

D.1 Empirical formulae of runner sizes

$$D_i = d_i + S \tag{D.1.1}$$

$$d_i = \frac{\sqrt{W_i} \times \sqrt[4]{L_i}}{3.7} \tag{D.1.2}$$

$$S = D_{min} - d_{min} \tag{D.1.3}$$

where D_i is the calculated runner diameter (mm) for part (i),

d_i is the relative runner diameter (mm) for part (i),

S is the constant value (mm),

W_i is the weight (g) of the part (i),

L_i is the runner flow length (mm) measured from the starting point of the sprue to part (i),

D_{min} is the milling cutter diameter for d_{min}, and d_{min} is the smallest relative runner diameter among all runners of the family mould.

Conditions:

1. The minimum value of D_i must be greater than or equal to 1.5 times of the part thickness (mm) to provide an adequate runner section for filling and packing of the part [3].
2. The constant value (S) will become zero if d_{min} is already greater than or equal to 1.5 times the part thickness (mm).
3. Runner diameter (D_i) must be corrected to the diameter of standard milling cutter range from 2 mm to 10 mm with an interval of 0.5 – 1.0 mm (up to a maximum of 13 mm for rigid PVCs and Acrylics is acceptable due to their high viscosity).
4. Maximum runner length for Ø2 must be under 50 mm (see Table D.1.1 for the runner length limitations of other runner diameters) to allow the molten material to continue its flow.
5. For rigid PVCs and Acrylics, increase the calculated diameter by 25%.
6. For mouldings weighing up to 200g and wall section less than 3 mm.

	Maximum Runner Length (mm)	
Runner Diameter (mm)	**Low Viscosity**	**High Viscosity**
2	50	25
3	100	50
6	200	100
9	280	150
13	330	175

Table D.1.1. Maximum runner lengths for specific diameters for plastic material with low and high viscosity[2]

$$\mathbf{D_{upstream}} = \sqrt[3]{\sum_{i=1}^{n} \mathbf{D_i}^3} \qquad \textbf{(D.1.4)}$$

Where D_i is the diameter of an individual downstream branch runner *i*, *n* is the number of branches and $D_{upstream}$ is the diameter of the runner section feeding the successive branch runners

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[2] *Table 1was developed by Luen Shing Tool limited based on senior mould designers' experience.*

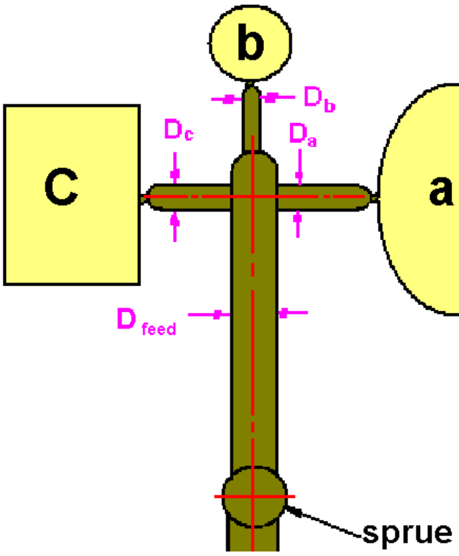


Figure D.1.1. Sizing variable diameter runners of a family mould.

For example, Figure D.1.1 shows a partial runner layout of a family mould. The smallest diameter of runner (D_a, D_b and D_c) attached to the gate of each part in a family mould can be calculated using empirical formulae **(D.1.1)**, **(D.1.2)** and **(D.1.3)** based on their weights and runner flow lengths. Given that D_a, D_b and D_c are 2.5 mm, 3.0 mm and 3.0 mm respectively, D_1 is equal to 4.1 mm calculated according to the empirical formula **(D.1.4)**. If a runner has one right angle turning, the diameter of the upstream runner segment will be equal to 1.2 times of that of its downstream one to compensate the pressure head loss at the right angle turning.

D.2 Empirical slider design rules

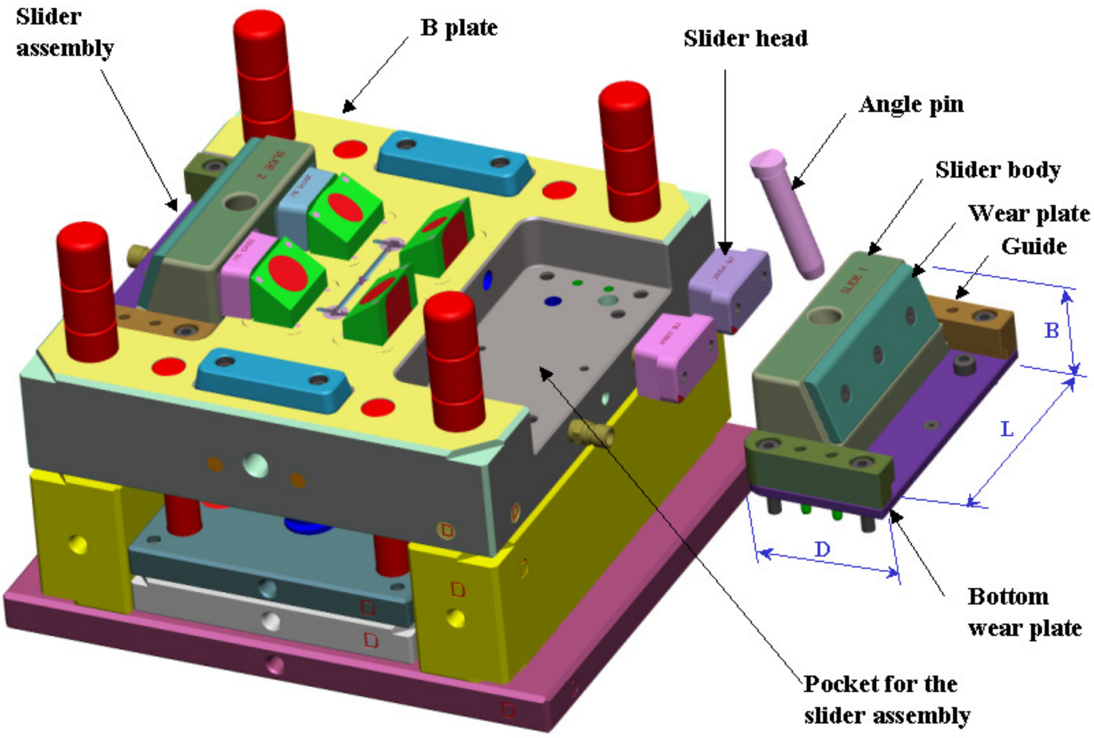
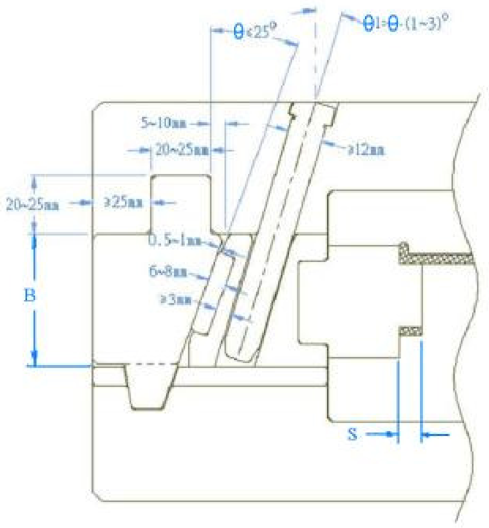
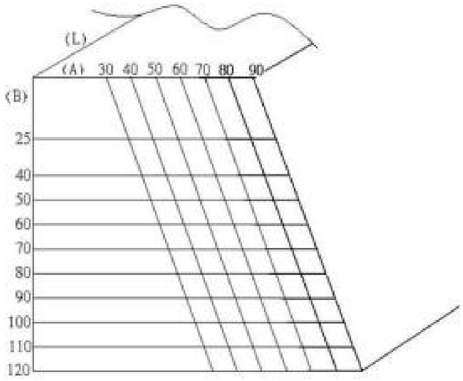


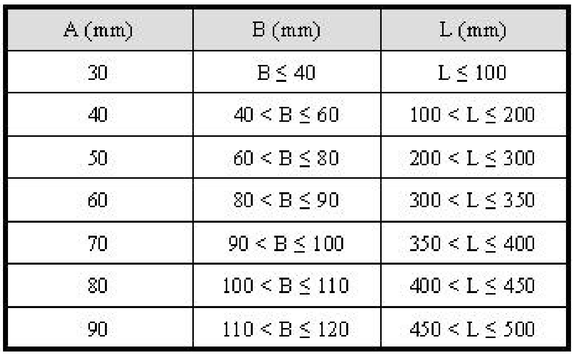
Figure D.2.1. The overall size of a slider assembly (Courtesy: Luen Shing Tools Limited)



$$B = S / \tan(\theta)$$

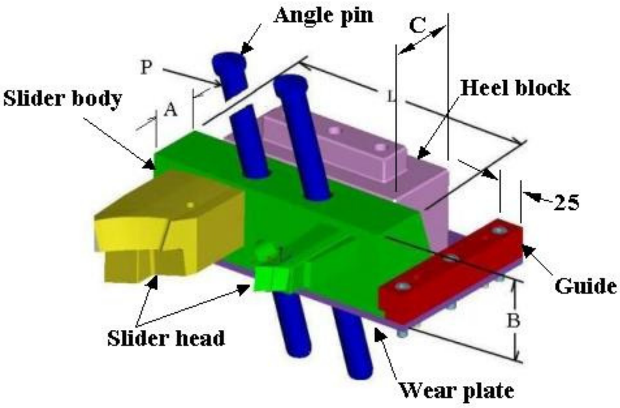
Figure D.2.2. Dimensional relations of a typical slider design (Courtesy: Luen Shing Tools Limited)

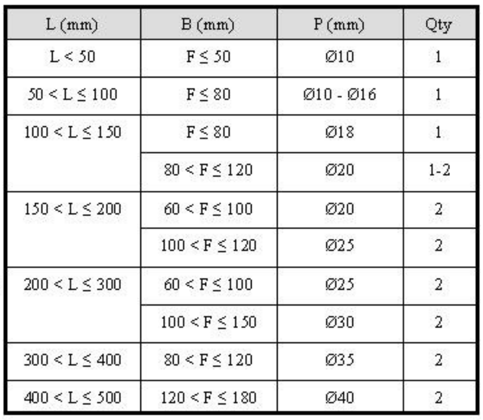




A (mm)	B (mm)	L (mm)
30	B ≤ 40	L ≤ 100
40	40 < B ≤ 60	100 < L ≤ 200
50	60 < B ≤ 80	200 < L ≤ 300
60	80 < B ≤ 90	300 < L ≤ 350
70	90 < B ≤ 100	350 < L ≤ 400
80	100 < B ≤ 110	400 < L ≤ 450
90	110 < B ≤ 120	450 < L ≤ 500

Figure D.2.3. Dimensional design rules of a slider body (Courtesy: Luen Shing Tools Limited)





L (mm)	B (mm)	P (mm)	Qty
L < 50	F ≤ 50	Ø10	1
50 < L ≤ 100	F ≤ 80	Ø10 - Ø16	1
100 < L ≤ 150	F ≤ 80	Ø18	1
	80 < F ≤ 120	Ø20	1-2
150 < L ≤ 200	60 < F ≤ 100	Ø20	2
	100 < F ≤ 120	Ø25	2
200 < L ≤ 300	60 < F ≤ 100	Ø25	2
	100 < F ≤ 150	Ø30	2
300 < L ≤ 400	80 < F ≤ 120	Ø35	2
400 < L ≤ 500	120 < F ≤ 180	Ø40	2

Figure D.2.4. Dimensional design rules of a slider assembly (Courtesy: Luen Shing Tools Limited)

For example, given that the required slider travelling distance (S) is 1.5 mm, the angle (θ) is 25 and the width of the slider (L) is 50, the height of the slider block (B) is equal to 11.2 mm calculated using the equation shown in Figure D.2.2. The calculated dimension (B) should be corrected to 25.0 mm because the recommended minimum height of the slider body is 25 mm. With reference to the table shown in Figure D.2.3, the dimension (B) is smaller than 40.0 mm and the dimension (L) is smaller than 100.0 mm, therefore the thickness of the slider block should be equal to 30.0 mm. The recommended minimum thickness of the heel block is 50.0 mm (25.0 mm + 20.0 mm + 5.0 mm) (see Figure D.2.2). Thus, the total thickness of the whole slider assembly (D) (see Figure D.2.1) is equal to 80.0 mm (30.0 mm + 50.0 mm). According to the table shown in Figure D.2.4, the recommended number of angle pins for this slider is one because the dimension (L) is smaller than 100.0 mm.

APPENDIX E - The weighted sum fitness function

$$\boxed{CP = \frac{K_m(C_m) + K_n(C_n) + K_r(C_r) + K_s(C_s) + K_j(C_j) + K_p(C_j)}{W_f(P_f) + W_r(P_r) + W_c(P_c) + W_d(P_d)}} \quad (E.1)$$

where P_f is the flow path balance performance value (%),

P_r is the runner diameter balance performance value (%),

P_c is the clamping force balance performance value (%),

P_d is the drop height balance performance value (%),

W_f is the weighting ratio of P_f,

W_r is the weighting ratio of P_r,

W_c is the weighting ratio of P_c,

W_d is the weighting ratio of P_d,

C_m is the cost of the mould base (HK$),

C_n is the cost of mould insert material (HK$),

C_r is the cost of runner material for the whole production volume (HK$),

C_s is the cost of sliders (HK$),

C_j is the cost of injection moulding (HK$),

K_m is the weighting ratio of C_m,

K_n is the weighting ratio of C_n,

K_r is the weighting ratio of C_r,

K_s is the weighting ratio of C_s,

K_j is the weighting ratio of C_j,

K_p is the penalty factor

$W_f + W_r + W_c + W_d = 1$,

$K_m + K_n + K_r + K_s + K_j = 1$

APPENDIX F – Experimental case study

F.1 Detail drawings of Parts 1-4

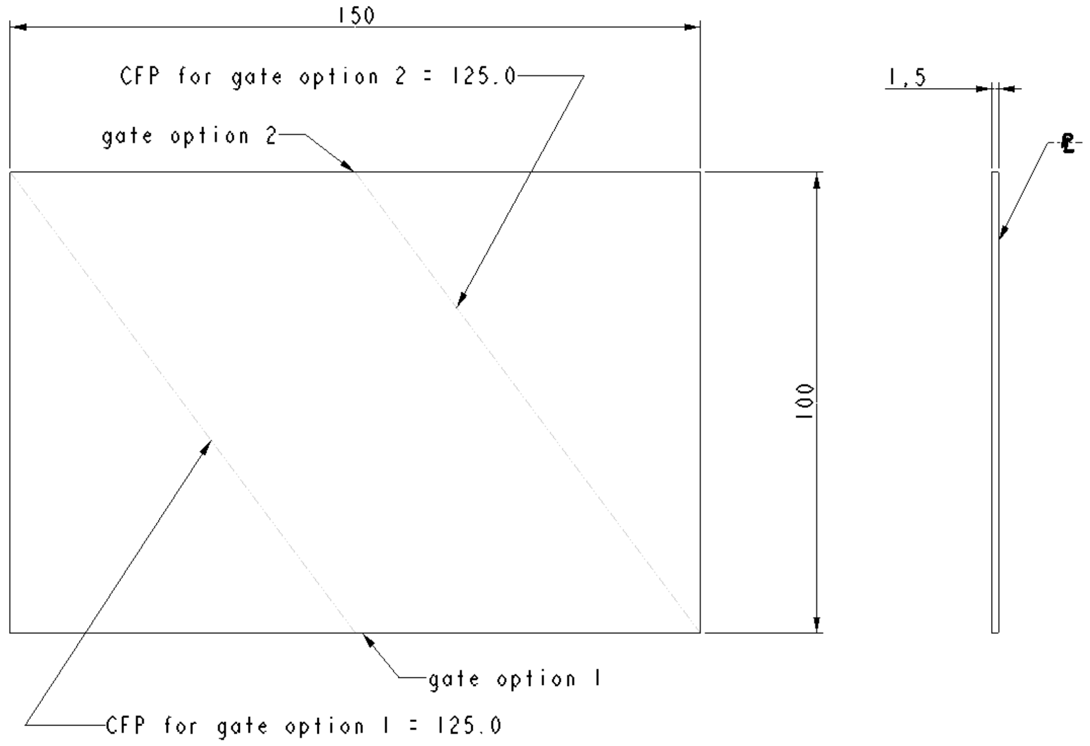


Figure F.1.1. Detail drawing of Part1

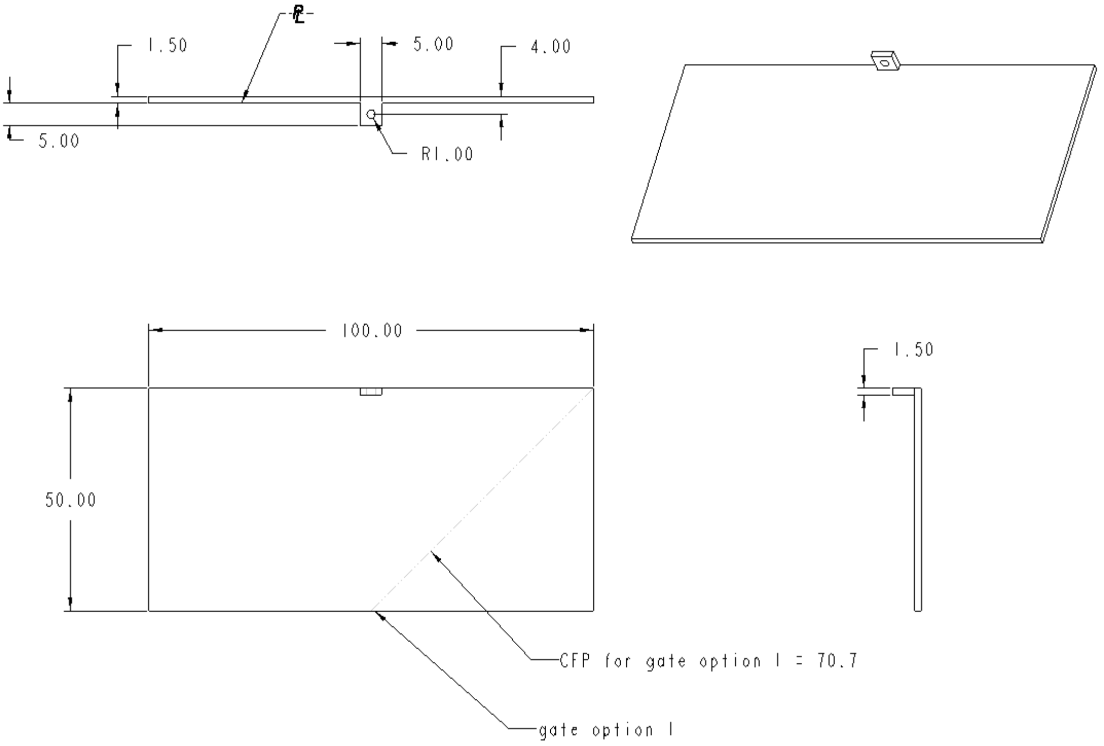


Figure F.1.2. Detail drawing of Part2

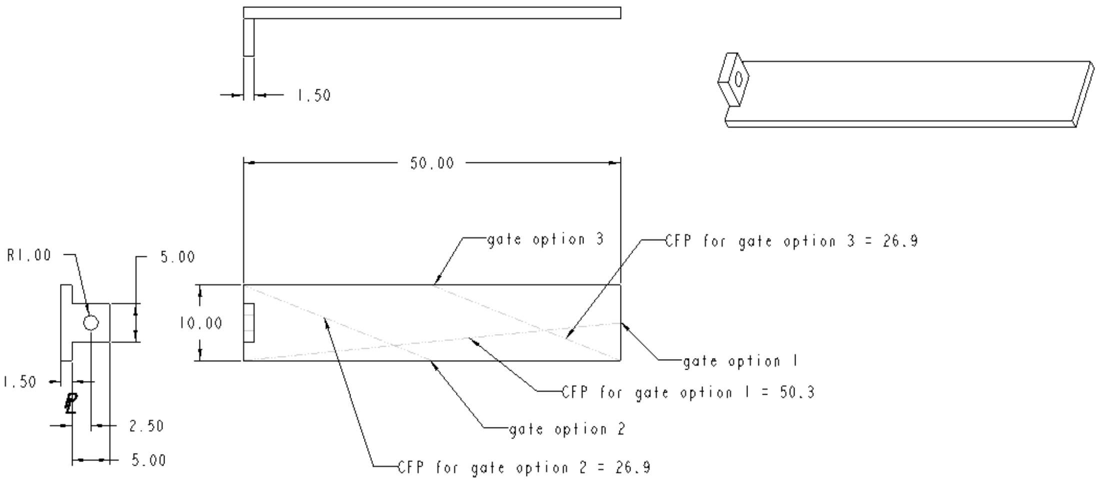


Figure F.1.3. Detail drawing of Part3

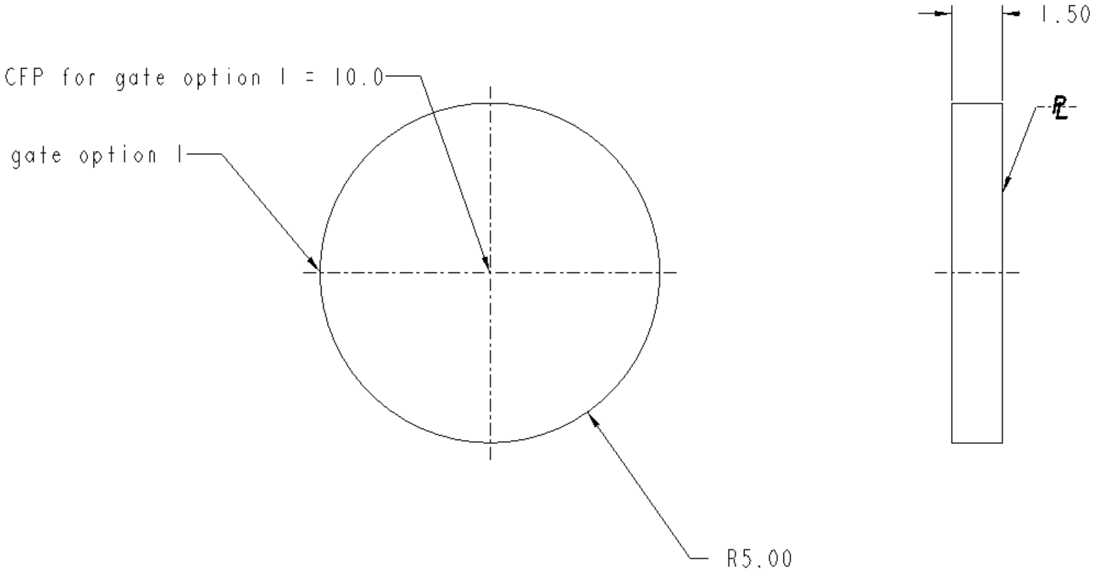


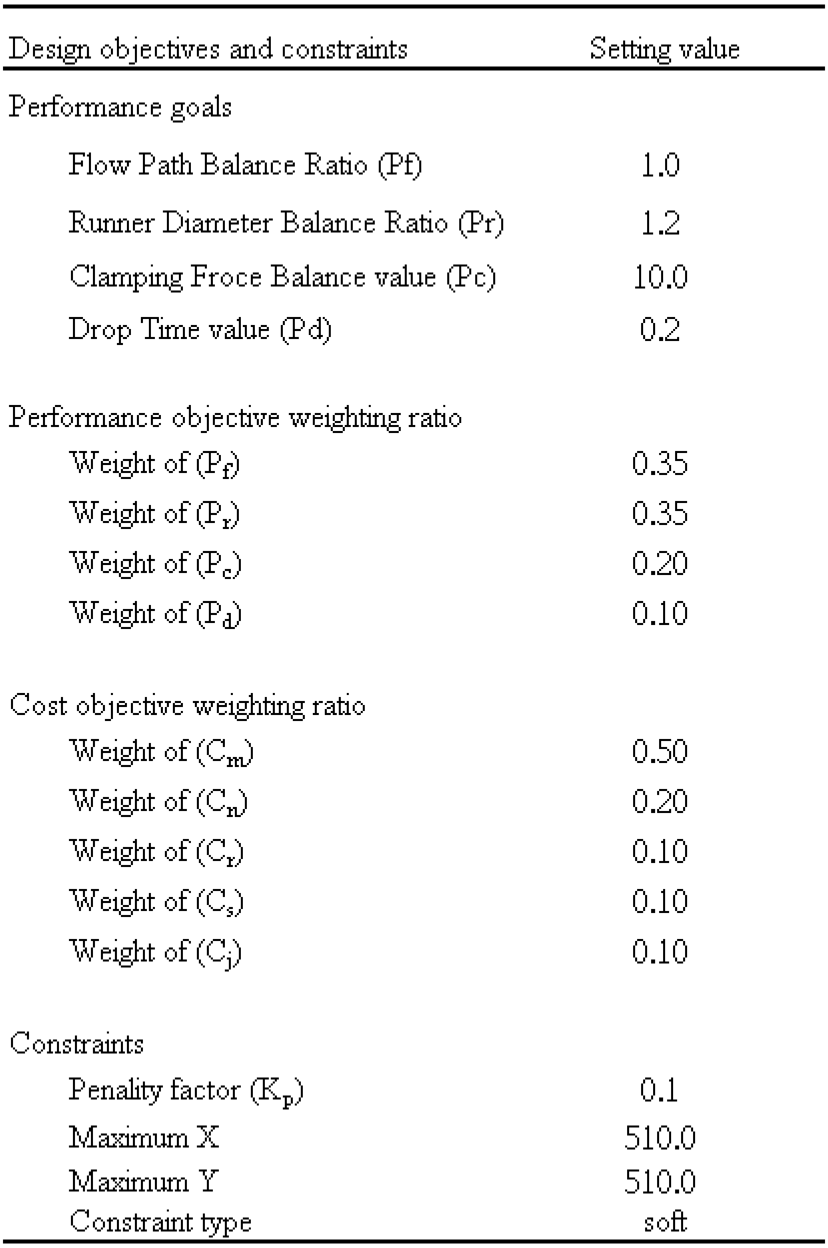
Figure F.1.4. Detail drawing of Part4

F.2 Specification of Parts 1-4

Name	Part 1	Part 2	Part 3	Part 4
Identity No.	1	2	3	4
part_shape_code	1	1	1	2
Px1	75.0	50.0	25.0	5.0
Px2	75.0	50.0	25.0	5.0
PX	150.0	100.0	50.0	10.0
Py1	50.0	25.0	5.0	5.0
Py2	50.0	25.0	5.0	5.0
PY	100.0	50.0	10.0	10.0
Pz1	0.0	5.0	5.0	0.0
Pz2	1.5	1.5	1.5	1.5
PZ	1.5	6.5	6.5	1.5
A (projected area)	15000.0	5000.0	500.0	78.5
W (weight)	23.49	7.86	0.82	0.12
wall_thk	1.5	1.5	1.5	1.5
type_of_gate	1	1	1	1
gate_data_list	{GATE_PNT0, GATE_PNT1}	{GATE_PNT0}	{GATE_PNT0, GATE_PNT1, GATE_PNT2}	{GATE_PNT0}
gate size				
H (depth)	0.9	0.9	0.9	0.9
B (width)	5.0	3.5	2.2	1.8
L (land)	0.5	0.5	0.5	0.5
slider_data_list				
slider_type	{}	{1}	{1}	{}
slider_csys	{}	{SLIDER1_CS0}	{SLIDER1_CS0}	{}
slider_dist	{}	{2.0}	{2.0}	{}
slider_insert_size_x1	{}	{1.0}	{1.0}	{}
slider_insert_size_x2	{}	{1.0}	{1.0}	{}
slider_insert_size_y1	{}	{1.0}	{1.0}	{}
slider_insert_size_y2	{}	{1.0}	{1.0}	{}
CFP_data_list	{125.0, 125.0}	{70.7}	{50.3,26.9,26.9}	{10.0}

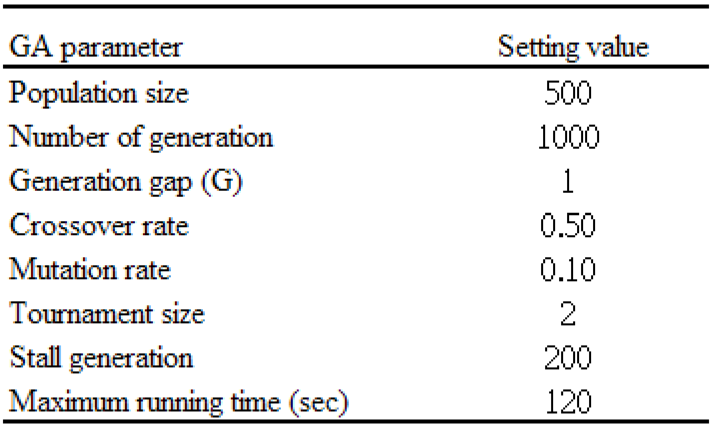
Table F.2.1. The specification of the moulding parts in this experimental case study

F.3 Optimisation parameters



Design objectives and constraints	Setting value
Performance goals	
Flow Path Balance Ratio (Pf)	1.0
Runner Diameter Balance Ratio (Pr)	1.2
Clamping Froce Balance value (Pc)	10.0
Drop Time value (Pd)	0.2
Performance objective weighting ratio	
Weight of (P_f)	0.35
Weight of (P_r)	0.35
Weight of (P_c)	0.20
Weight of (P_d)	0.10
Cost objective weighting ratio	
Weight of (C_m)	0.50
Weight of (C_n)	0.20
Weight of (C_r)	0.10
Weight of (C_s)	0.10
Weight of (C_j)	0.10
Constraints	
Penality factor (K_p)	0.1
Maximum X	510.0
Maximum Y	510.0
Constraint type	soft

Table F.3.1. The setting of design objectives and constraints in this experimental case study



GA parameter	Setting value
Population size	500
Number of generation	1000
Generation gap (G)	1
Crossover rate	0.50
Mutation rate	0.10
Tournament size	2
Stall generation	200
Maximum running time (sec)	120

Table F.3.2. The initial setting of GA parameters in this experimental case study

F.4 Experiment results

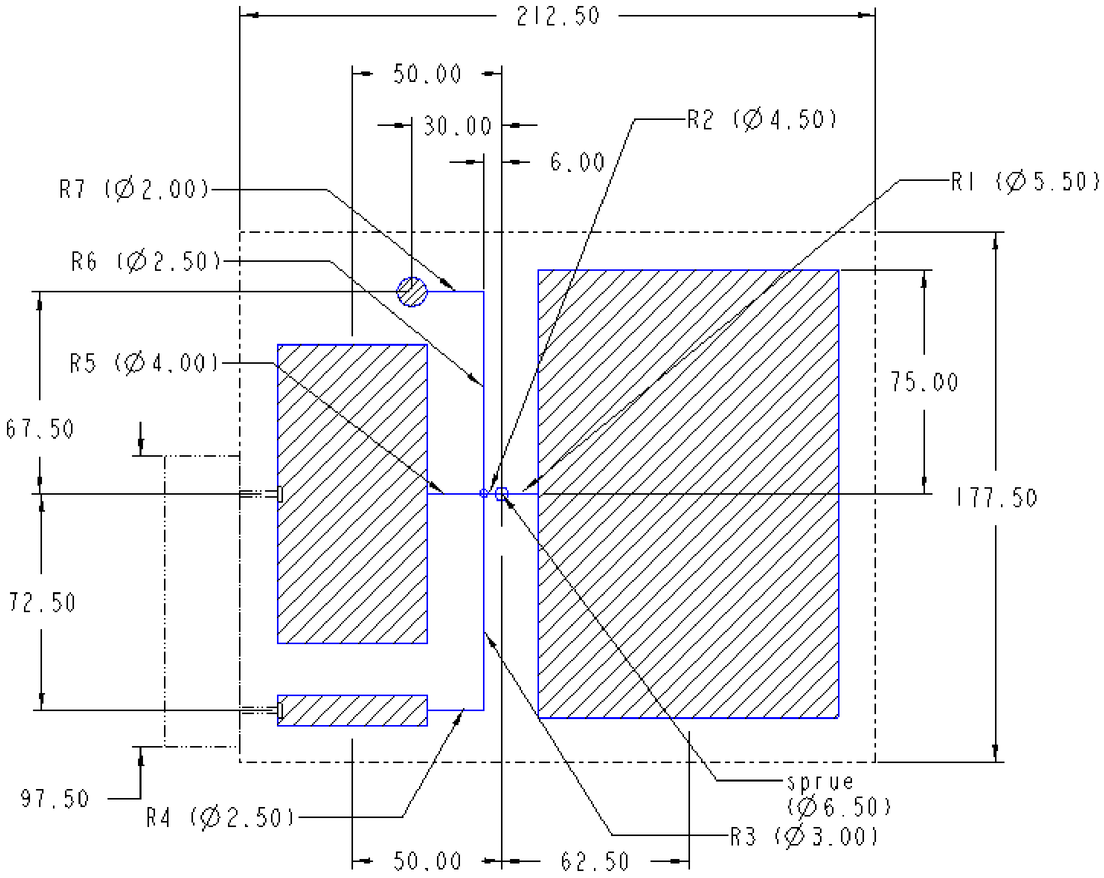


Figure F.4.1. The FMCRLD drawing created by Designer A

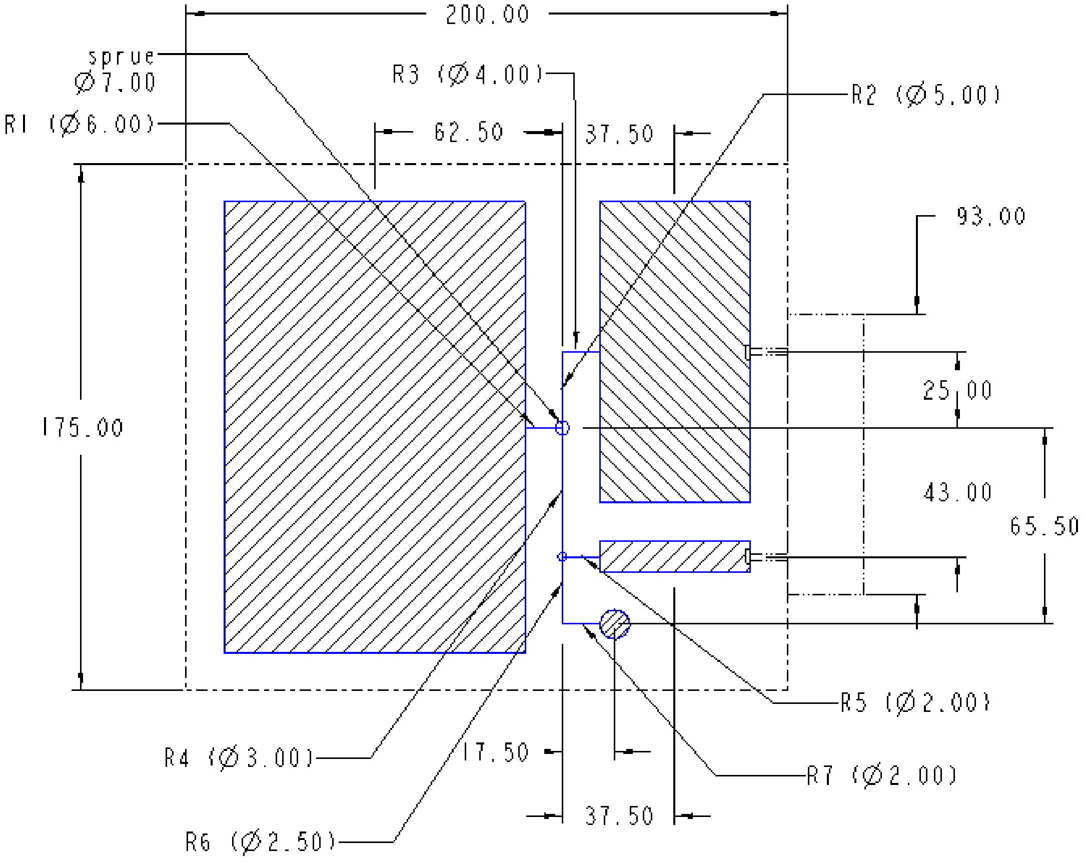


Figure F.4.2. The FMCRLD drawing created by Designer B

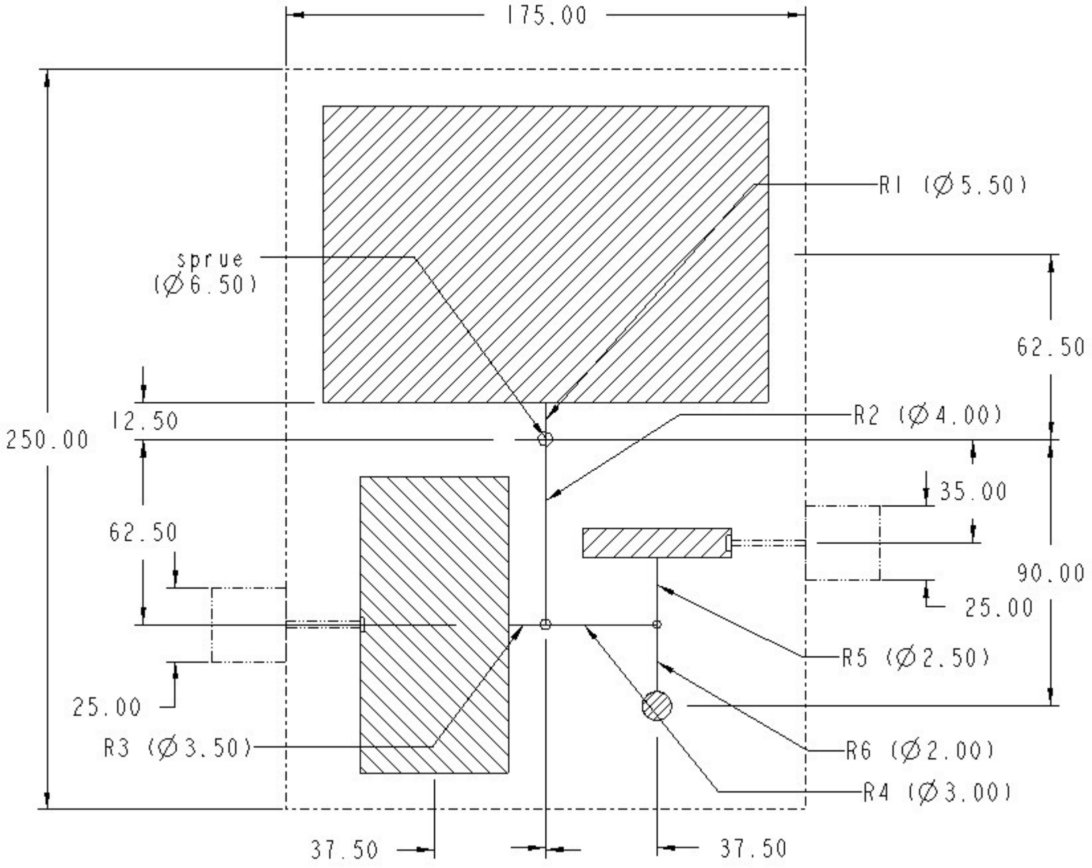


Figure F.4.3. The FMCRLD drawing created by Designer C

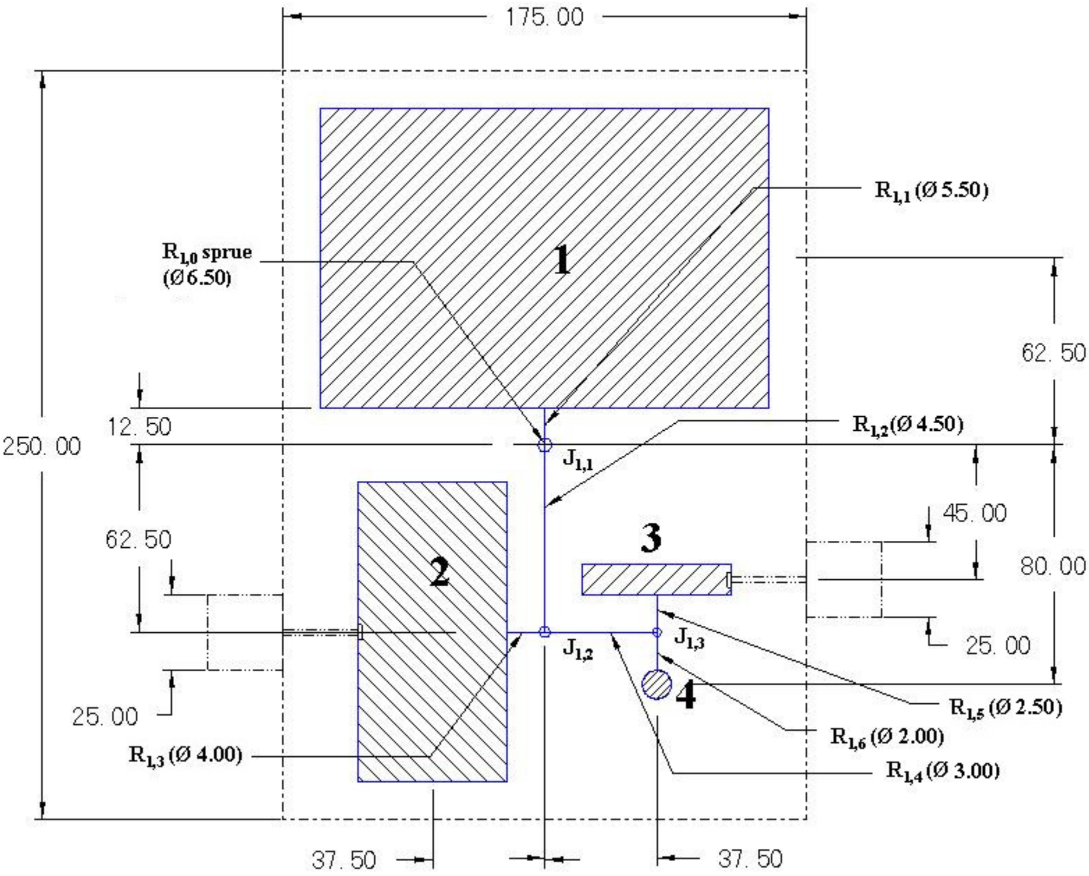


Figure F.4.4. The FMCRLD drawing generated by the ICMLDS prototype

APPENDIX G – Implementation case study I

G.1 Detail drawings of Parts A-G

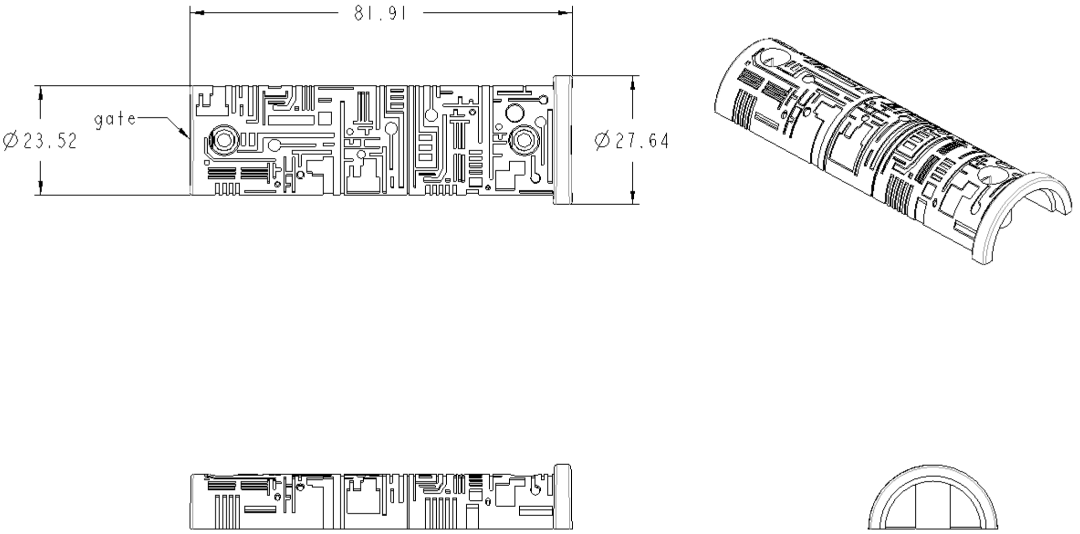


Figure G.1.1. Detail drawing of Part A

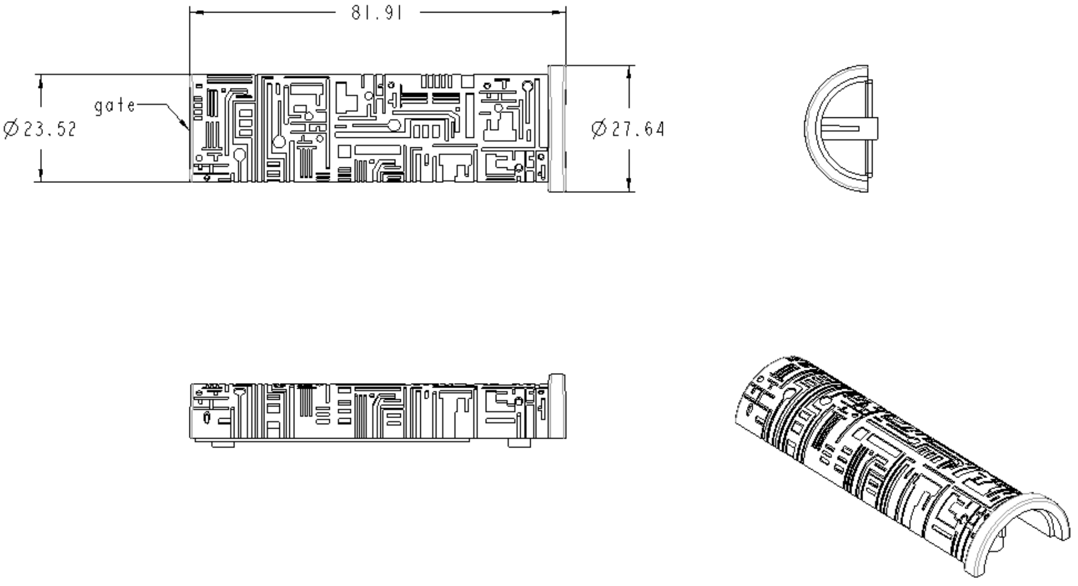


Figure G.1.2. Detail drawing of Part B of case study I

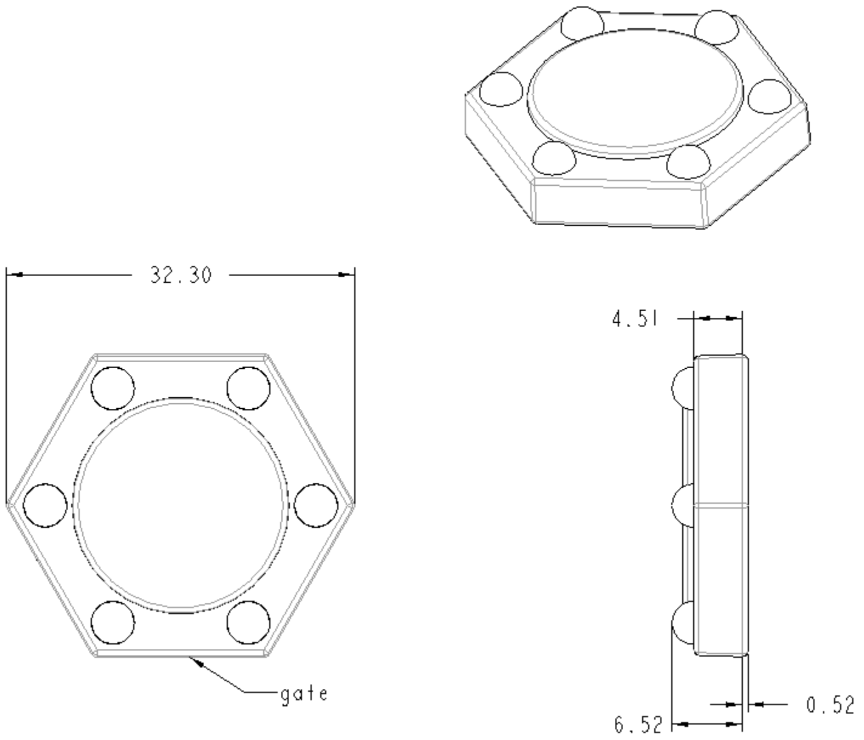


Figure G.1.3. Detail drawing of Part C of case study I

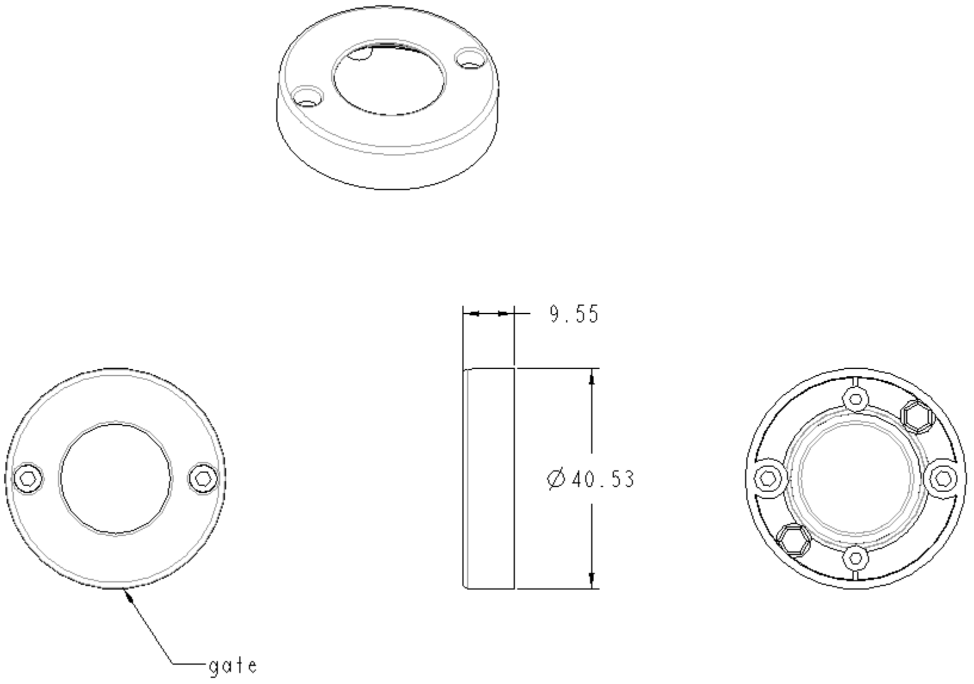


Figure G.1.4. Detail drawing of Part D of case study I

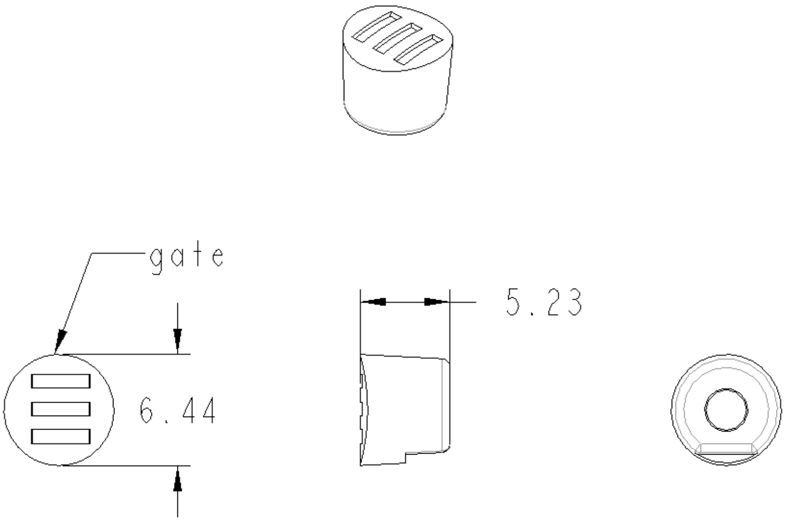


Figure G.1.5. Detail drawing of Part E and F of case study I

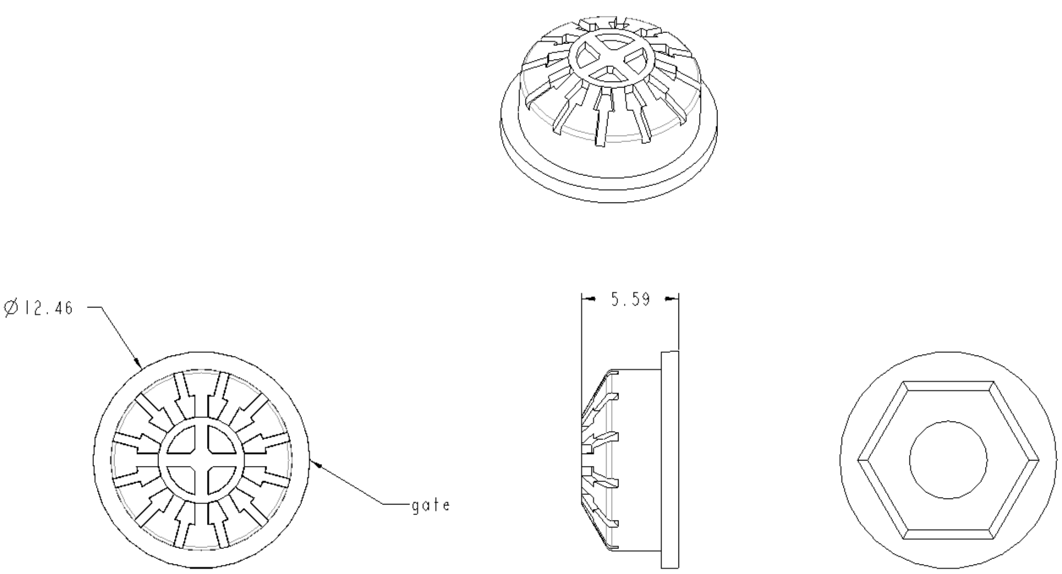
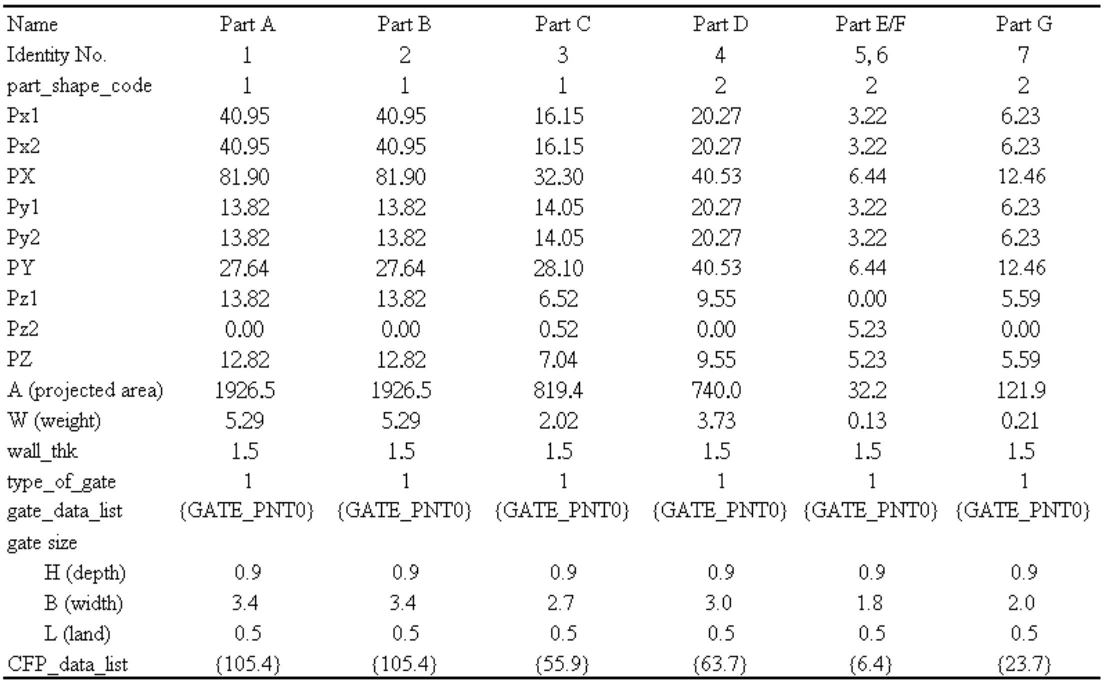


Figure G.1.6. Detail drawing of Part G of case study I

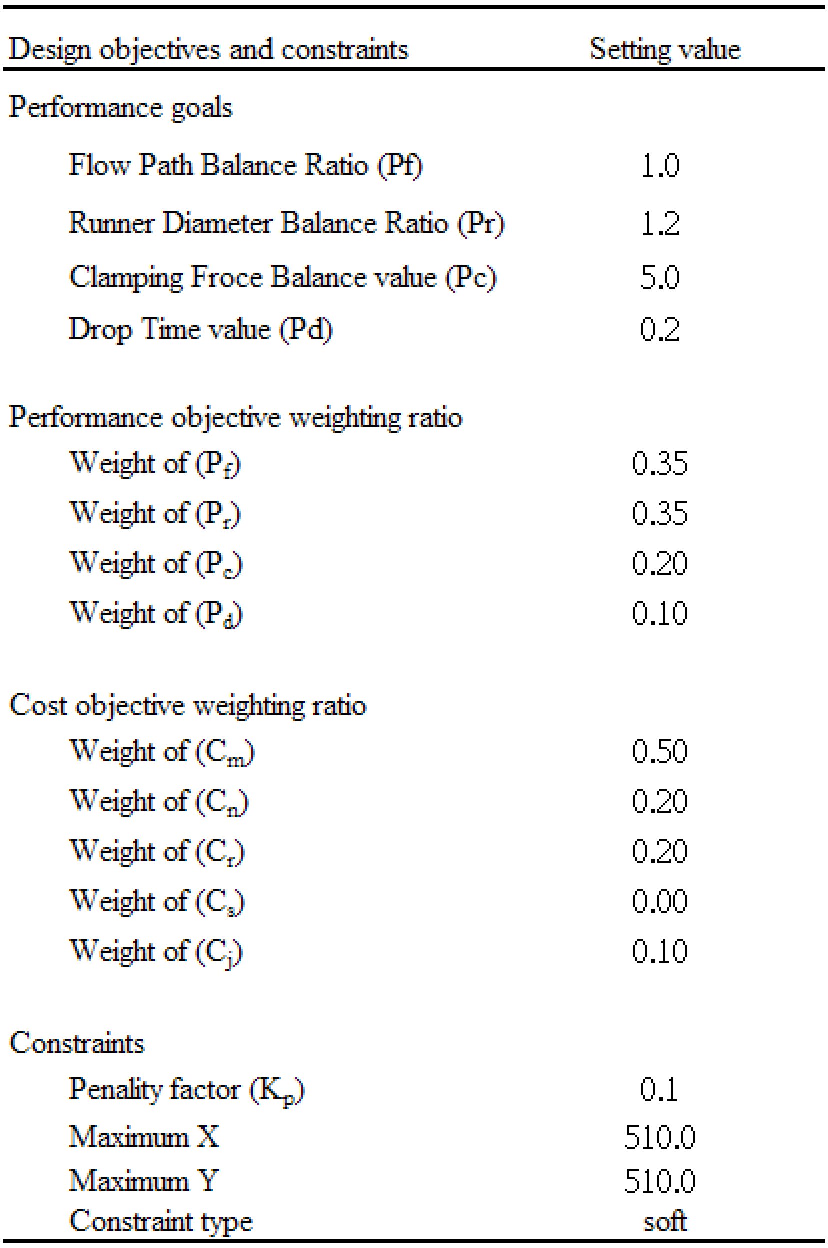
G.2 Specification of Parts A-G



Name	Part A	Part B	Part C	Part D	Part E/F	Part G
Identity No.	1	2	3	4	5, 6	7
part_shape_code	1	1	1	2	2	2
Px1	40.95	40.95	16.15	20.27	3.22	6.23
Px2	40.95	40.95	16.15	20.27	3.22	6.23
PX	81.90	81.90	32.30	40.53	6.44	12.46
Py1	13.82	13.82	14.05	20.27	3.22	6.23
Py2	13.82	13.82	14.05	20.27	3.22	6.23
PY	27.64	27.64	28.10	40.53	6.44	12.46
Pz1	13.82	13.82	6.52	9.55	0.00	5.59
Pz2	0.00	0.00	0.52	0.00	5.23	0.00
PZ	12.82	12.82	7.04	9.55	5.23	5.59
A (projected area)	1926.5	1926.5	819.4	740.0	32.2	121.9
W (weight)	5.29	5.29	2.02	3.73	0.13	0.21
wall_thk	1.5	1.5	1.5	1.5	1.5	1.5
type_of_gate	1	1	1	1	1	1
gate_data_list	{GATE_PNT0}	{GATE_PNT0}	{GATE_PNT0}	{GATE_PNT0}	{GATE_PNT0}	{GATE_PNT0}
gate size						
H (depth)	0.9	0.9	0.9	0.9	0.9	0.9
B (width)	3.4	3.4	2.7	3.0	1.8	2.0
L (land)	0.5	0.5	0.5	0.5	0.5	0.5
CFP_data_list	{105.4}	{105.4}	{55.9}	{63.7}	{6.4}	{23.7}

Table G.2.1. The specification of the moulding parts in case study I

G.3 Optimisation parameters



Design objectives and constraints	Setting value
Performance goals	
Flow Path Balance Ratio (Pf)	1.0
Runner Diameter Balance Ratio (Pr)	1.2
Clamping Froce Balance value (Pc)	5.0
Drop Time value (Pd)	0.2
Performance objective weighting ratio	
Weight of (P_f)	0.35
Weight of (P_r)	0.35
Weight of (P_c)	0.20
Weight of (P_d)	0.10
Cost objective weighting ratio	
Weight of (C_m)	0.50
Weight of (C_n)	0.20
Weight of (C_r)	0.20
Weight of (C_s)	0.00
Weight of (C_j)	0.10
Constraints	
Penality factor (K_p)	0.1
Maximum X	510.0
Maximum Y	510.0
Constraint type	soft

Table G.3.1. The setting of design objectives and constraints in case study I

G.4 Mould drawing

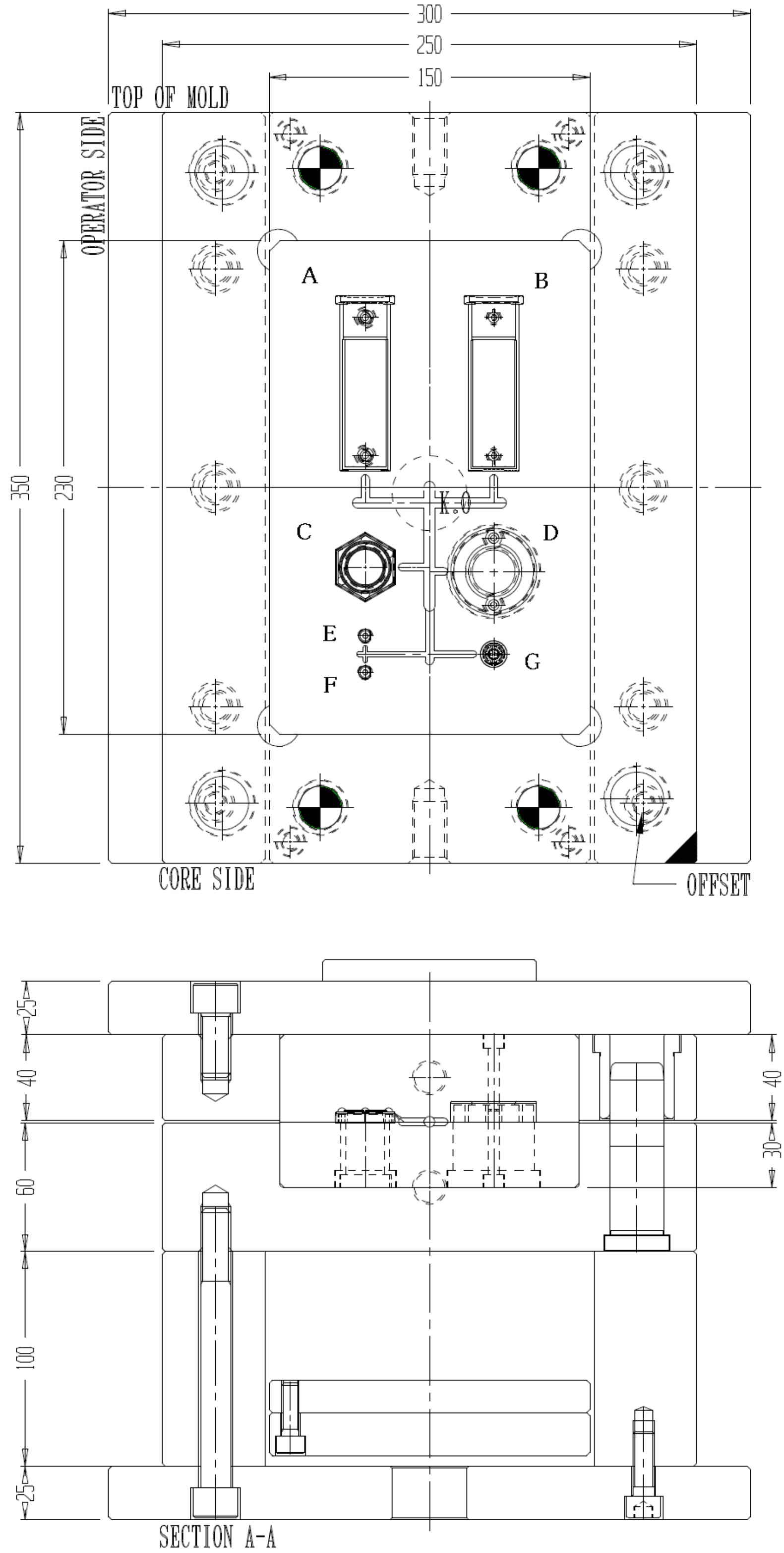


Figure G.4.1. Mould assembly drawing generated by the ICMLDS prototype in case study I

G.5 Mould flow filling analysis results

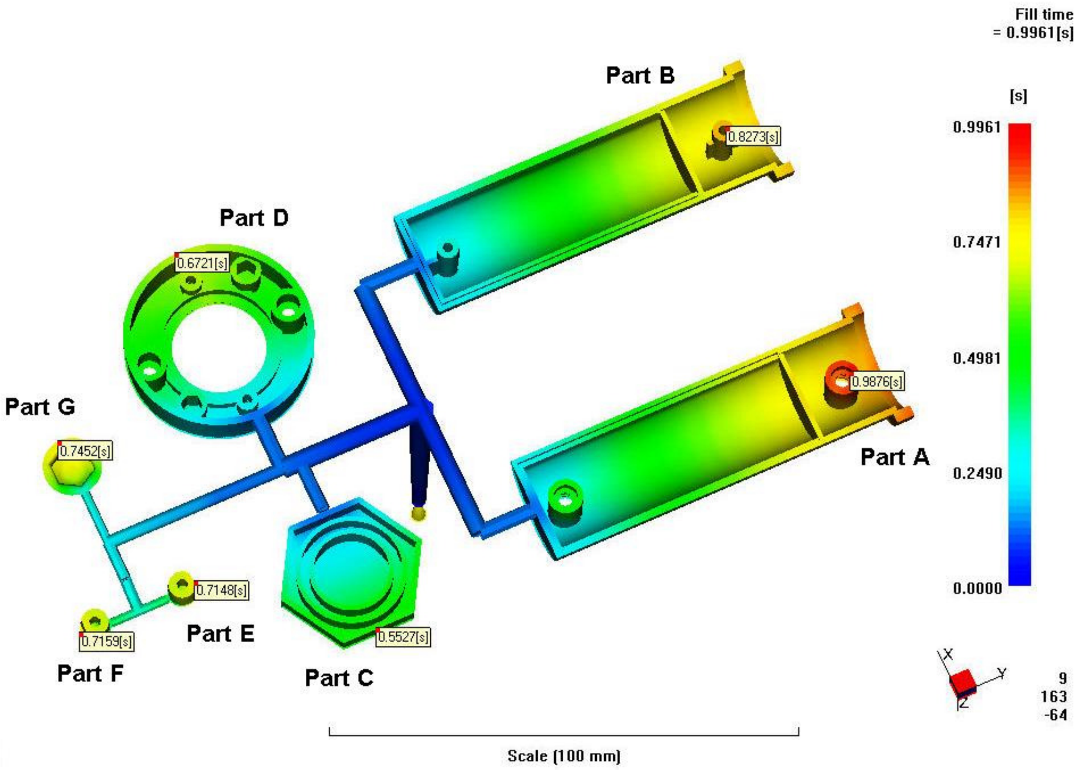


Figure G.5.1. Filling analysis result of layout 1 in case study I

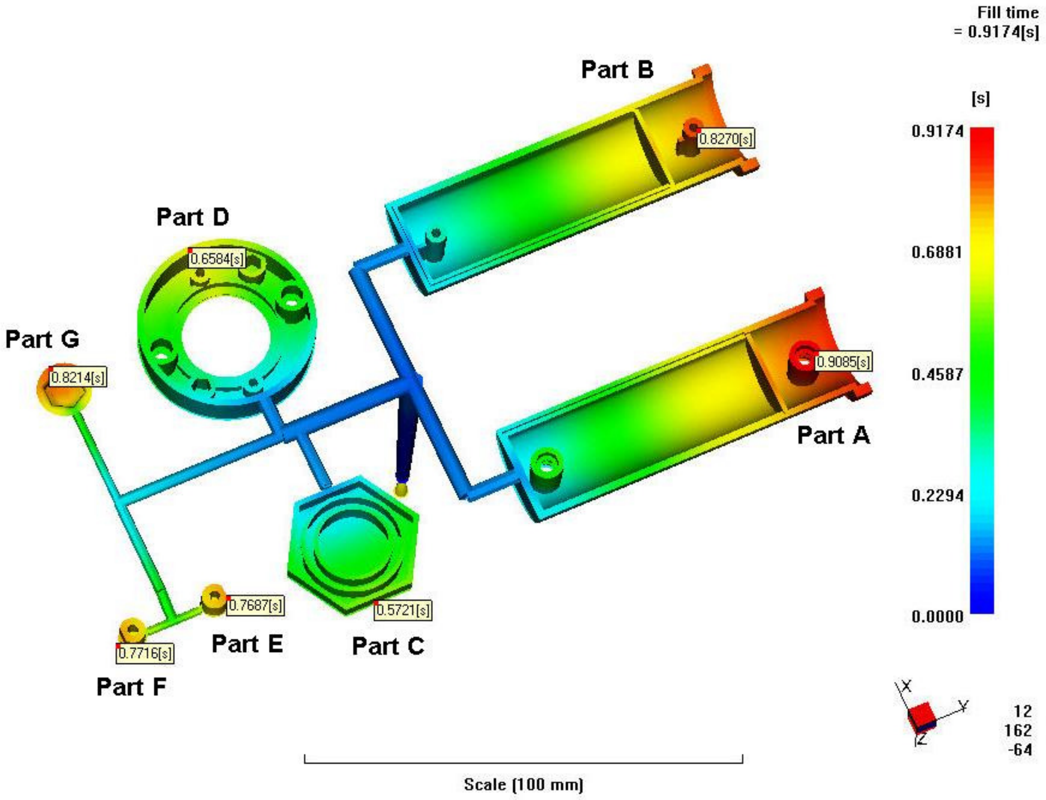
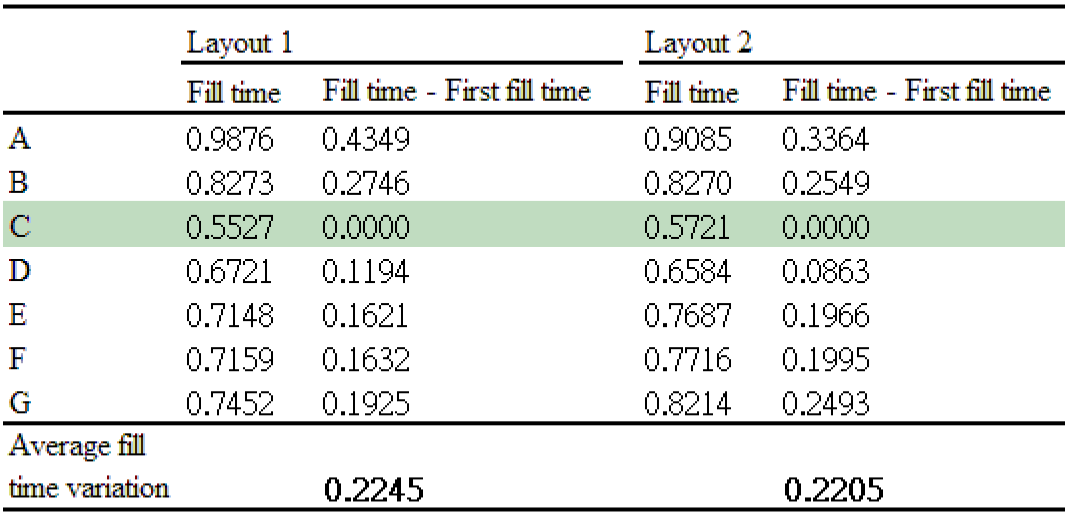


Figure G.5.2. Filling analysis result of layout 2 in case study I



	Layout 1		Layout 2	
	Fill time	Fill time - First fill time	Fill time	Fill time - First fill time
A	0.9876	0.4349	0.9085	0.3364
B	0.8273	0.2746	0.8270	0.2549
C	0.5527	0.0000	0.5721	0.0000
D	0.6721	0.1194	0.6584	0.0863
E	0.7148	0.1621	0.7687	0.1966
F	0.7159	0.1632	0.7716	0.1995
G	0.7452	0.1925	0.8214	0.2493
Average fill time variation		**0.2245**		**0.2205**

Table G.5.1. The comparison of the average fill time variation between layouts 1 and 2

Figures G.5.1 and G.5.2 show the filling analysis results of layouts 1 and 2. The average fill time variation of layouts 1 and 2 are calculated in Table G.5.1. The fill analysis results showed that part C was filled first in both cases. Therefore, the fill time of part C was used as the first fill time datum to calculate the average fill time variation across all parts of the layout. By comparison, the average fill time variation of layout 1 (0.2245 seconds) is larger than that of layout 2 (0.2205 seconds). In other words, the fill balance performance of layout 2 is better than that of layout 1. This is because the runner flow lengths of relatively smaller parts C, E, F and G are intentionally increased in layout 2 in an attempt to balance the longer CFP lengths of parts A, B and D. These results can further prove that P_f can be used to evaluate the fill balance performance of FMCRLD efficiently.

APPENDIX H – Implementation case study II

H.1 Detail drawings of Parts A-G

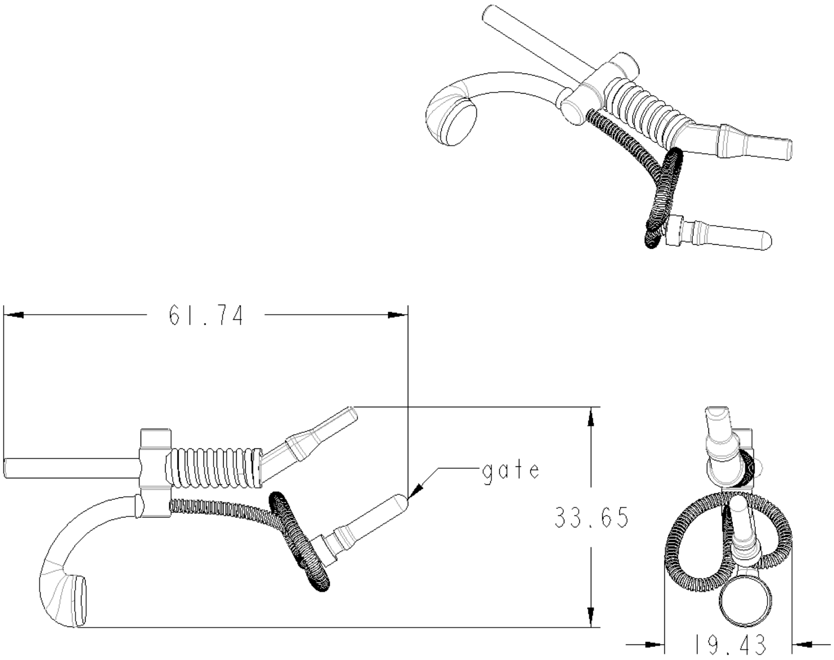


Figure H.1.1. Detail drawing of Part A of case study II

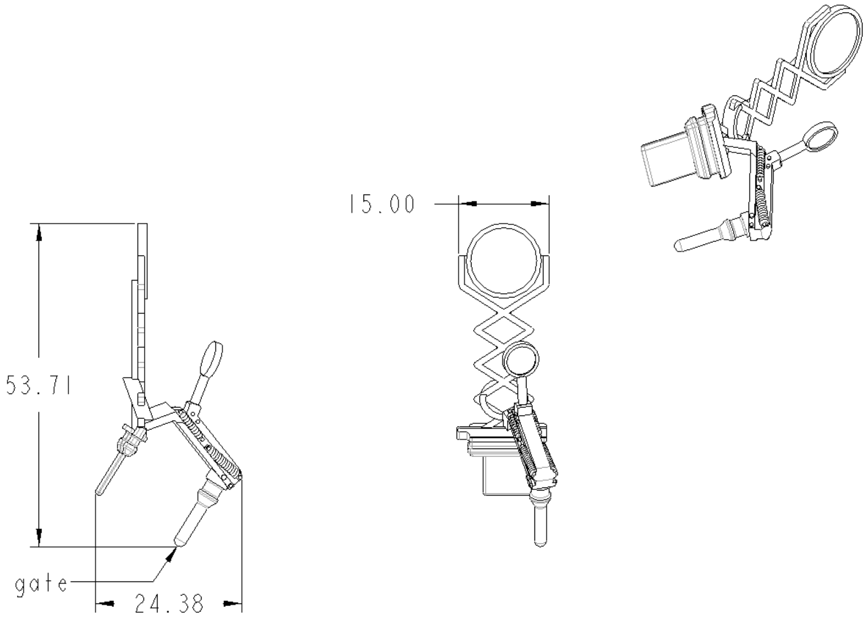


Figure H.1.2. Detail drawing of Part B of case study II

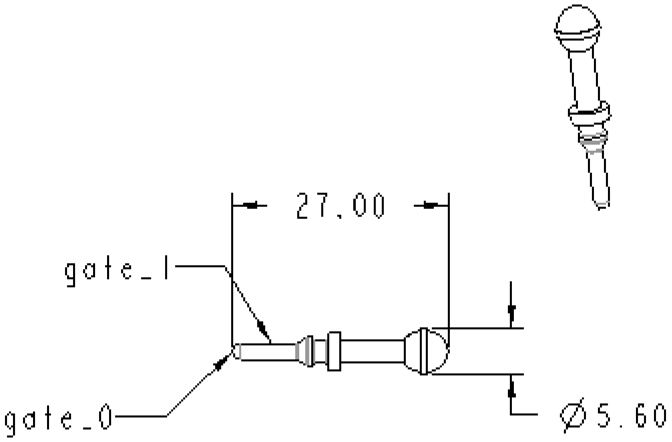


Figure H.1.3. Detail drawing of Part C of case study II

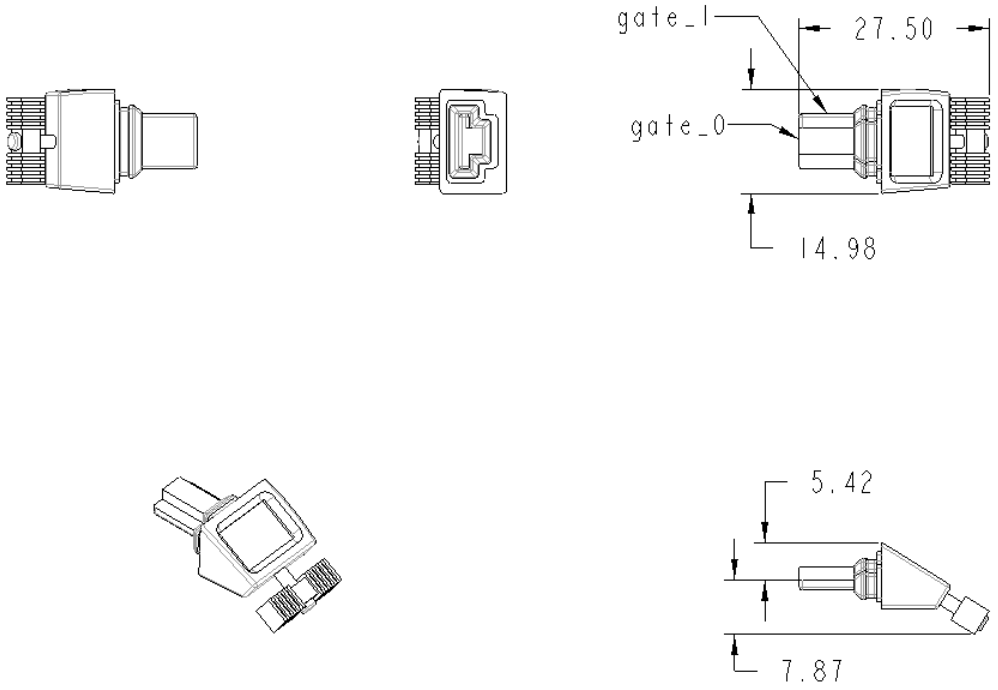


Figure H.1.4. Detail drawing of Part D of case study II

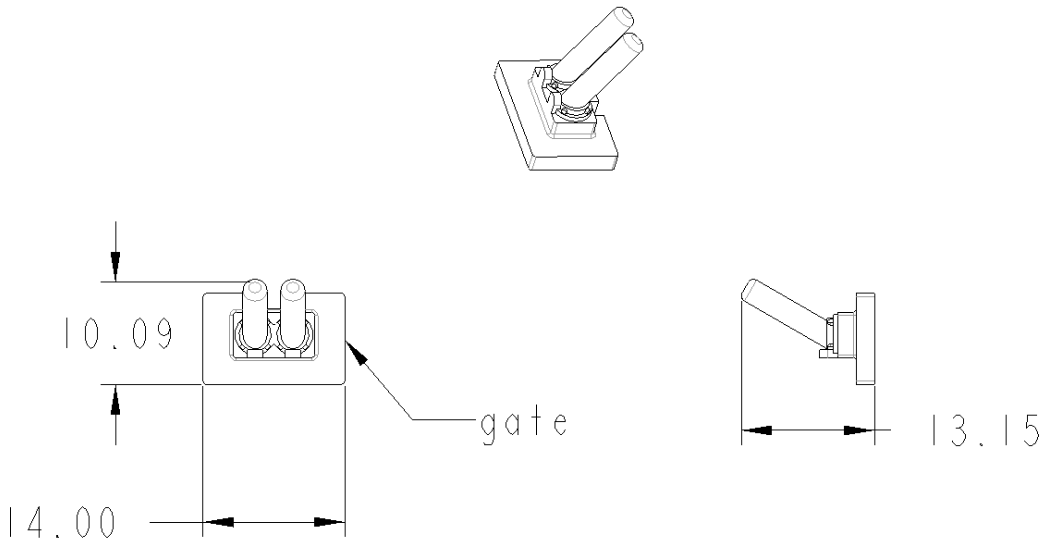


Figure H.1.5. Detail drawing of Part E of case study II

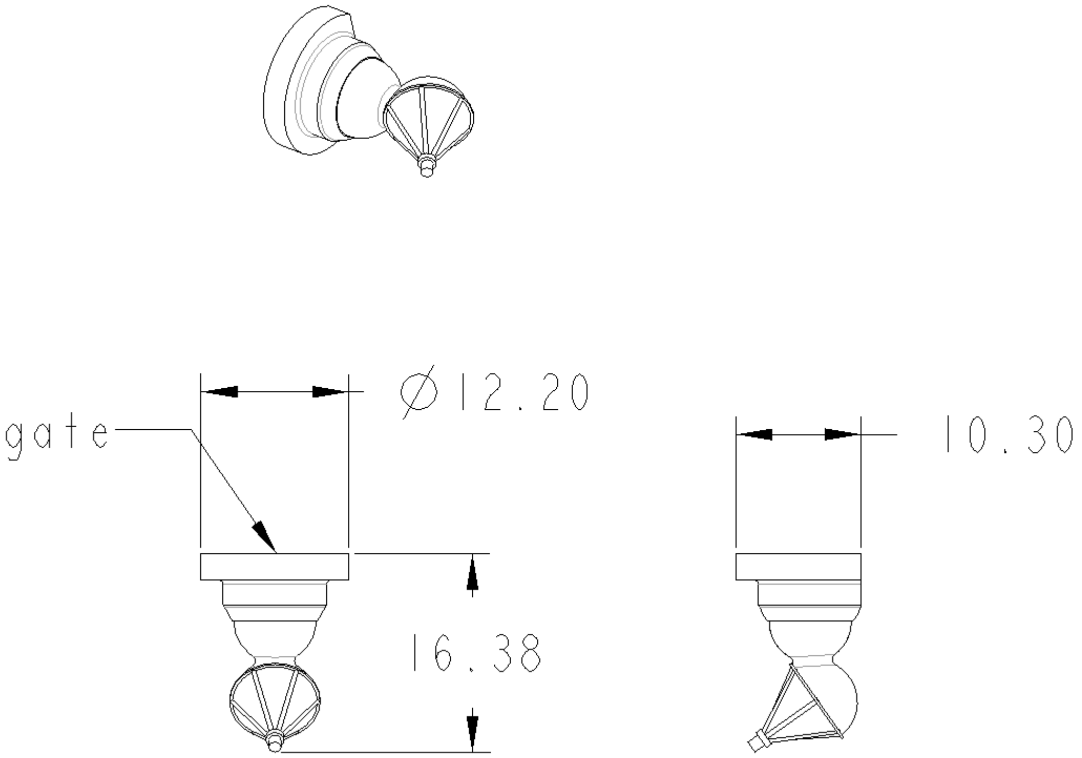


Figure H.1.6. Detail drawing of Part F of case study II

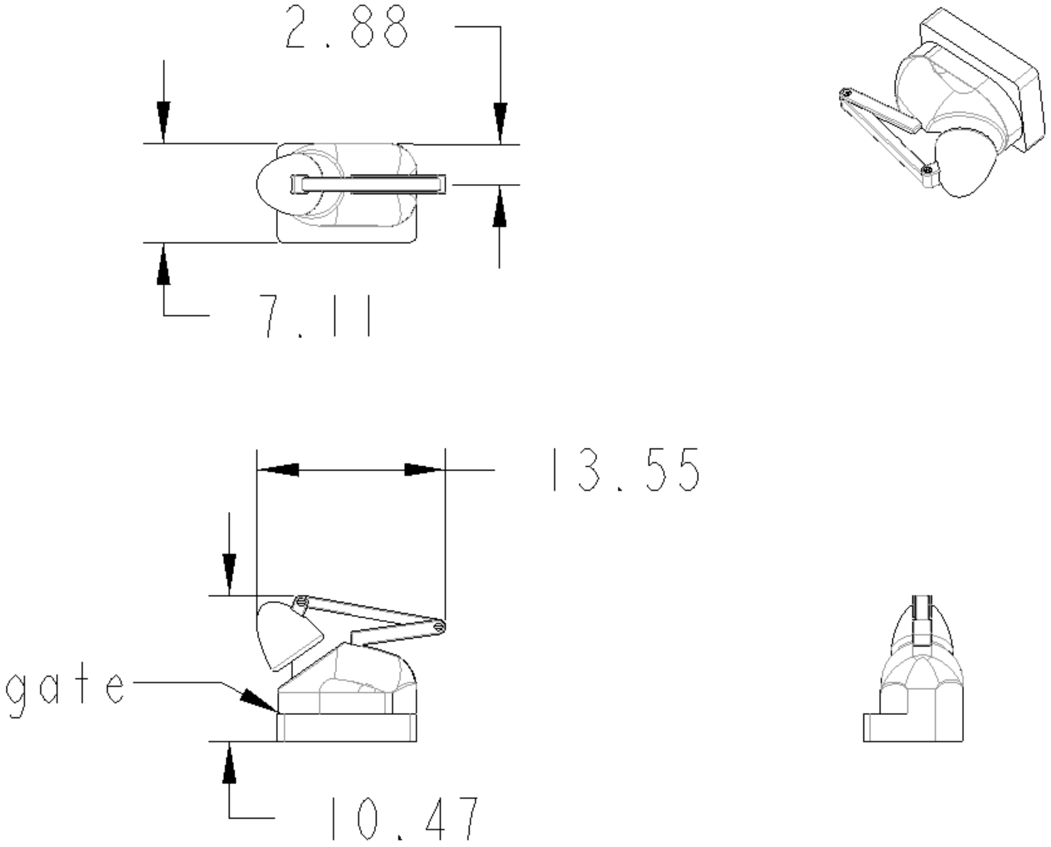


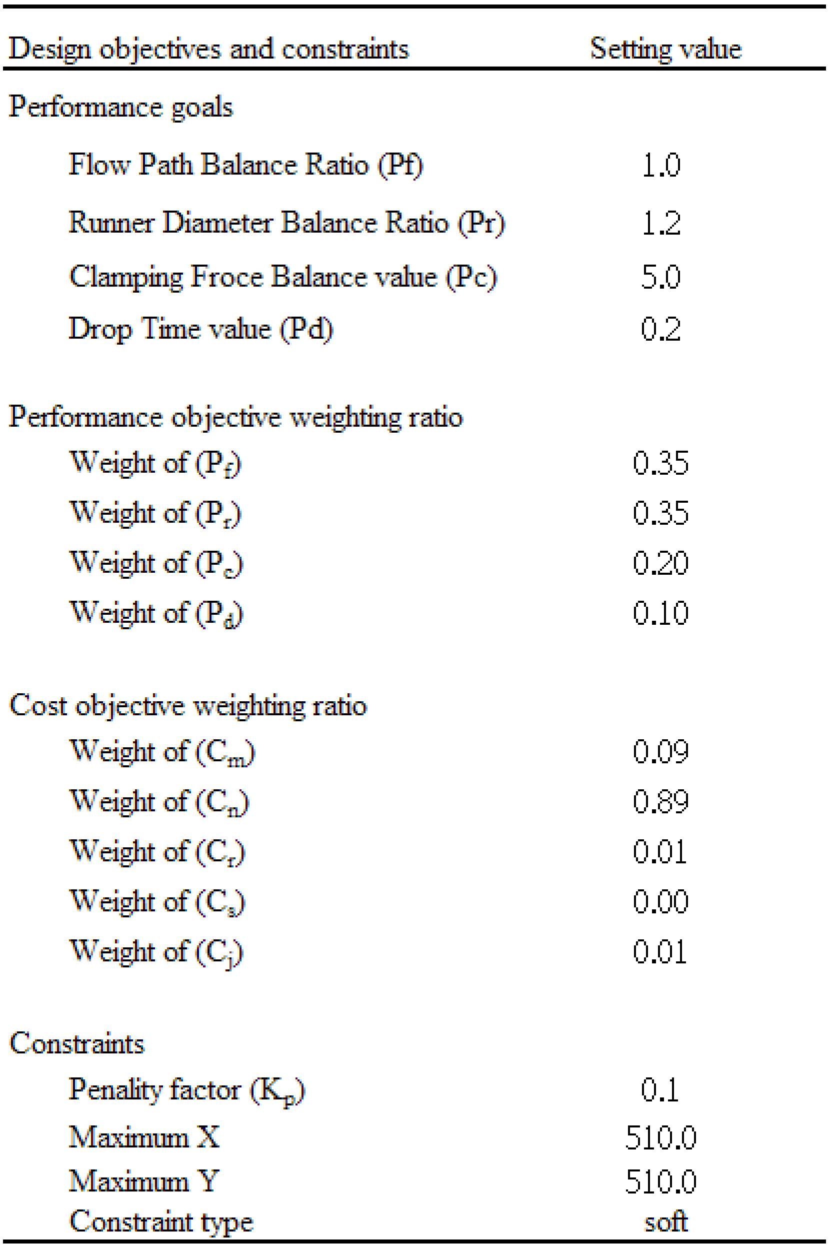
Figure H.1.7. Detail drawing of Part G of case study II

H.2 Specification of Parts A-G

Name	Part A	Part B	Part C	Part D	Part E	Part F	Part G
Identity No.	1	2	3	4	5	6	7
part_shape_code	1	1	1	1	1	1	1
Px1	31.0	27.0	13.5	14.0	7.0	8.0	7.0
Px2	31.0	27.0	13.5	14.0	7.0	8.0	7.0
PX	62.0	54.0	27.0	28.0	14.0	16.0	14.0
Py1	17.0	12.0	3.0	7.5	5.0	5.0	5.0
Py2	17.0	12.0	3.0	7.5	5.0	5.0	5.0
PY	34.0	24.0	6.0	15.0	10.0	10.0	10.0
Pz1	9.7	5.0	3.0	5.0	0.0	6.0	3.0
Pz2	9.7	10.0	3.0	8.0	13.0	6.0	4.0
PZ	19.4	15.0	6.0	13.0	13.0	12.0	7.0
A (projected area)	823.0	328.0	162.0	420.0	140.0	160.0	140.0
W (weight)	1.57	0.98	0.23	1.29	0.40	0.55	0.41
wall_thk	1.5	1.5	1.5	3.0	1.5	3.0	3.0
type_of_gate	1	1	1	1	1	1	1
gate size							
H (depth)	1.2	1.2	1.2	1.2	1.2	1.2	1.2
B (width)	2.4	2.4	2.4	2.4	2.4	2.4	2.4
L (land)	0.6	0.6	0.6	0.6	0.6	0.6	0.6
gate_data_list	{GATE_PNT0}	{GATE_PNT0}	{GATE_PNT0,GATE_PNT1}	{GATE_PNT0, GATE_PNT1}	{GATE_PNT0}	{GATE_PNT0}	{GATE_PNT0}
CFP_data_list	{84.0}	{68.0}	{27.0, 23.4}	{27.5, 24.3}	{14}	{16.4}	{13.5}

Table H.2.1. The specification of the moulding parts in case study II

H.3 Optimisation parameters



Design objectives and constraints	Setting value
Performance goals	
Flow Path Balance Ratio (Pf)	1.0
Runner Diameter Balance Ratio (Pr)	1.2
Clamping Froce Balance value (Pc)	5.0
Drop Time value (Pd)	0.2
Performance objective weighting ratio	
Weight of (P_f)	0.35
Weight of (P_r)	0.35
Weight of (P_c)	0.20
Weight of (P_d)	0.10
Cost objective weighting ratio	
Weight of (C_m)	0.09
Weight of (C_n)	0.89
Weight of (C_r)	0.01
Weight of (C_s)	0.00
Weight of (C_j)	0.01
Constraints	
Penality factor (K_p)	0.1
Maximum X	510.0
Maximum Y	510.0
Constraint type	soft

Table H.3.1. The setting of design objectives and constraints in case study II

H.4 Mould drawing

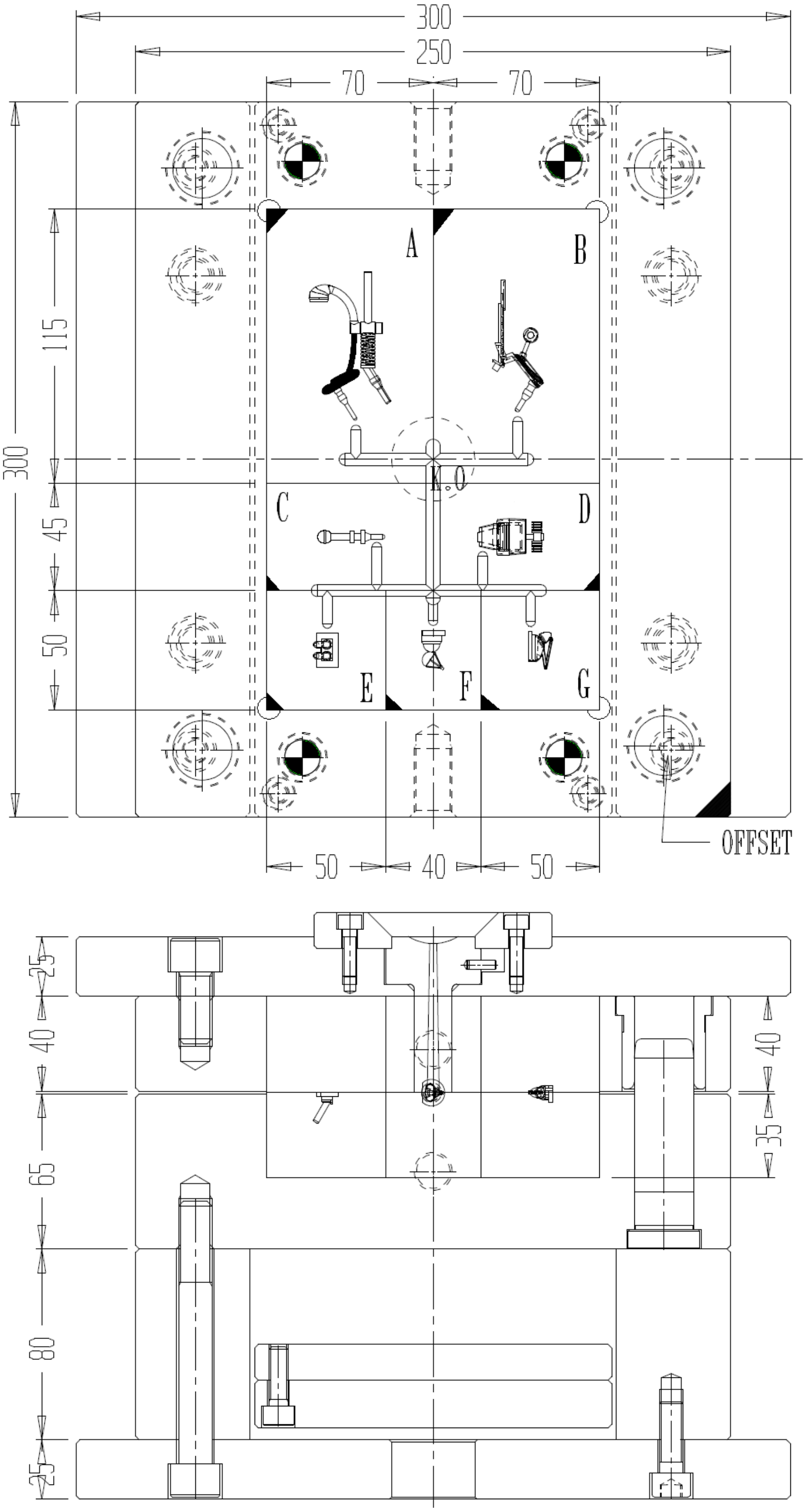


Figure H.4.1. Mould assembly drawing generated by the ICMLDS prototype in case study II