Chapter 2

Literature Review

Previous research attempts on various aspects of the die-casting die-design are discussed in this chapter. Some research papers related to the injection moulding process are also discussed along-with the die-casting due to strong similarity between both the processes. Most of the research for die-casting die-design is focused on issues such as determination of parting direction, parting line, parting surface, undercut feature recognition, and design of single-cavity die [17-29], whereas lesser attention has been given to the design of multi-cavity die-casting dies. The literature review presented in this chapter is divided into four categories (i) cavity layout design, (ii) core, cavity and side-core design, (ii) gating system design, and (iv) computer-aided die-design systems. A tabular summary of the previous research attempts on each of the above category is also presented for readers’ ready reference.

The chapter is organized into the following sections. Section 2.1 discusses the literature on cavity layout design for multi-cavity dies. Section 2.2 discusses the literature on core, cavity and side-core design for multi-cavity die-casting dies. Section 2.3 discusses the literature on gating system design for multi-cavity die-casting dies. Section 2.4 discusses the literature on computer-aided die-design systems for the die-casting process. Section 2.5 presents: (i) a summary of research gaps between the industry needs and state of the art, and (ii) a discussion on objectives of the thesis.
2.1 Cavity Layout Design for Multi-Cavity Dies

The cavity layout design has two stages, the first stage is of design of cavity, which takes care of the shrinkage and draft allowance, and the second stage is of layout design, which determines the number of cavities and arranges them in the die. This section discusses previous research attempts related to both the stages of the cavity layout design for multi-cavity dies.

2.1.1 Cavity design

In case of multi-cavity die-design also, a good design of the single cavity is essential to achieve success in the computer-aided die-design process. Provision of shrinkage and draft allowances to the part model is essential for design of a cavity [12, 30]. In the following paragraphs, a discussion on the literature related to the shrinkage and draft allowances is made.

Chan et al. [31] presented an interactive knowledge-based injection moulding die-design system. The system takes the material shrinkage rate information from the material library. The material for the cavity is considered to be generic. Once the shrinkage rate is determined, the part model is reconstructed to account for the material shrinkage. However, the system does not support the application of draft.

Choi et al. [32] developed a system for automation of die-casting die-design activities. The system designs a die following three steps: (i) cast (part model) input, (ii) material selection, and (iii) shrinkage application. The architecture of the system is shown in Figure 2.1. However, the system has the limitations that the shrinkage factor is not linked with the selected part material, and it needs to be entered manually.
Woon and Lee [33] proposed a die-casting die-design system that helps a designer to design a die beginning with a part product model. The project manager module of the system deals with up-loading of the part product model and setting the shrinkage rate. The user needs to enter the part material, shrinkage rate, and reference position to scale the part model. However, the system does not have the facility to provide draft, and selection of the shrinkage factor need to be done interactively by the expert.

Wu et al. [34] developed a die-design system that helps to design the gating system. The data initialization module of the system deals with loading of the part model, and inputting material properties and machine parameters. To obtain accurate die cavity dimensions, the part model is scaled by a factor of 1.05 to 1.07 to account for shrinkage allowance. However, the system does not have the provision to provide draft and shrinkage factor, can be done manually by the designer.

Reddy et al. [30] developed guidelines, and an algorithm for automatic provisioning of draft angle on part surfaces. They suggested a draft value of one degree.
for external, and two degree for internal surfaces of the part. However, their work is limited to axis-symmetric components only, and the draft angle determined by the system does not take into account the part material.

Lee and Lee [35] developed a knowledge-based system for injection moulding die-design. The developed system helps in providing draft allowance on cylindrical and conical surfaces of the part. However, the system is not capable to determine draft allowance for different types of walls, which needs to be entered manually.

Yan et al. [36] proposed a system that automatically provides draft allowance on the part surfaces; the draft allowance is based on control point translation idea. As per the control point translation idea, the draft angle should vary according to height of the vertical faces. In actual practice the draft angle also varies with the type of wall, such as outside, inside, and a hole. However, the system is not able to provide appropriate draft angle depending on the type of wall.

2.1.2 Layout design

The layout design can be divided into two stages. First, optimal but feasible number of cavities is determined, followed by arrangement of cavities in the selected die-base. This section discusses previous research attempts related to both the aspects of the layout design.

Ye et al. [37] presented a system for initial design of an injection moulding die. The system determines parting line for a part followed by determination of required number of cavities. A feature box is designed that records the information about the gate and geometric features of the part, and helps in automatic design of the cavity layout. The system makes use of user provided information about the layout pattern and orientation of each cavity. The injection moulding die-base, which is used for
accommodating the cavities, is up-loaded automatically by the system. This system is incorporated in a previously developed system named IMOLD [38]. However, the system neither considers the required clearance details, nor helps to select the layout pattern.

**Low and Lee** [39] proposed a system to design the cavity layout for plastic injection moulding dies by controlling the geometrical parameters, which uses a cavity layout design standard template. Each standardized template has two parts: a configuration database and a layout design table. The configuration database consists of all the standard layout configurations. Each layout configuration has its own layout design table that carries the geometrical parameters. However, the system does not consider the undercut features and non-standard configurations of cavity layout patterns.

**Low and Lee** [40, 41] presented a system for rapid realization of initial design of injection moulding dies. The system uses a technical discussion checklist, which is used as an overall standard template. Information related to the part material and its shape, number of cavities and types of gating system used, etc. are entered into a standard template by the user. The number of cavities needs to be entered manually. Some of the limitations of the system are: (i) only standard cavity layout patterns are used, (ii) undercut features are not considered, and (ii) no provision of clearances to accommodate feed system.

**Hu and Masood** [42] developed an intelligent cavity layout design system (ICLDS) for multiple cavity injection moulding dies that assists the die designers in cavity layout design. The knowledge-based system makes use of the case-based and rule-based reasoning to arrive at the cavity layout solution, which is also shown
graphically. It takes the number of cavities as an input from the user. However, the system is not able to extract geometrical information from CAD model of the part.

**Reddy et al.** [30] developed a software package that provides intelligent assistance in several tasks involved in the design of die-casting dies. These include material selection, parting line location, gating parameters calculation, and die layout design. The die layout design module determines the number of cavities based on the selected machine and displays alternative cavity layouts to the user. However, the system has the limitation that it can handle only axis-symmetric shape components, and considers circular type layout pattern only.

**Fuh et al.** [12] developed a die-casting die-design system which has several functional modules as add-on applications of Unigraphics software [16]. These modules include data initialization, cavity layout design, and gating system design. The number of cavities is determined based on the selected machine. However, selection of the cavity layout pattern is not automated and requires human expertise.

**Choi et al.** [32] developed a die-casting die-design system based on the AutoCAD platform. The system automates the runner and gate design of the die. A module named cavity block design module determines required size of the die block taking into account the part size. However, the developed system can handle single-cavity die only.

**Chan et al.** [31] developed an interactive injection moulding die-design system, which makes use of part design information along-with the die manufacturing knowledge. The die-design module of the developed system deals with the design of cavity layout. The number of cavities is determined using empirical relations of the machine technical data, delivery date and part manufacturing cost; however, part
geometrical constraints are not accounted. Furthermore, the system considers balanced cavity layout patterns only and lacks in the level of automation.

**Woon and Lee** [33] proposed a system named *DiWorks* that helps the die designer to design a die-casting die beginning with a CAD file of the part. The layout design module of the system allows the die designer to select the number of cavities, and their layout pattern. However, the system does not perform these activities automatically and requires human expertise.

**Wu et al.** [34] developed a die-design system that helps to realize automatic generation of the gating system of a die-casting die. The design module of the system deals with data initialization and cavity layout design. The system suggests the number of cavities on the basis of selected machine type, delivery requirement and part geometric constraints; however the part manufacturing cost is not considered. Furthermore, orientation of the cavities is done by the designer, and is not automated.

**Dewhurst and Blum** [43] presented a methodology for cost estimation of die-cast parts by considering processing time and die manufacturing cost. They derived an expression for optimum number of cavities by considering cost factor only. However, other factors, such as part geometrical limitations, and delivery date are not considered.

**Madan et al.** [44] presented a knowledge-based computer-aided system to estimate the manufacturing cost of die-cast parts. The system determines the number of cavities by considering the factors, such as available manufacturing resources, die-casting machine constraints, and part geometric features. However, determination of number of cavities based on delivery date is not considered.

A summary of the literature on cavity layout design for multi-cavity dies is presented in Table 2.1.
<table>
<thead>
<tr>
<th>Author</th>
<th>Issues Address</th>
<th>Methodology</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reddy et al.[30]</td>
<td>Number of cavities;</td>
<td>Empirical relations and use of</td>
<td>Limited to axis-symmetric shape components; Only</td>
</tr>
<tr>
<td></td>
<td>Cavity layout design</td>
<td>material, gating and pattern database.</td>
<td>circular type layout pattern is considered.</td>
</tr>
<tr>
<td>Fuh et al.[12]</td>
<td>Cavity design;</td>
<td>Application of empirical relations.</td>
<td>Selection of cavity layout requires human interface.</td>
</tr>
<tr>
<td></td>
<td>Cavity layout design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chan et al.[31]</td>
<td>Number of cavities;</td>
<td>Based on empirical relations;</td>
<td>Selection of the cavity layout is based on designer's experience.</td>
</tr>
<tr>
<td></td>
<td>Cavity design;</td>
<td>knowledge database.</td>
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</tr>
<tr>
<td></td>
<td>Cavity layout design</td>
<td></td>
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</tr>
<tr>
<td>Choi et al.[32]</td>
<td>Cavity design;</td>
<td>Rule-based approach and use of</td>
<td>Limited to simple shape components; Does not</td>
</tr>
<tr>
<td></td>
<td>Cavity layout design</td>
<td>database.</td>
<td>consider undercut features.</td>
</tr>
<tr>
<td>Woon and Lee [33]</td>
<td>Number of cavities;</td>
<td>SolidWorks API; feature-based and</td>
<td>Selection of number of cavities and layout pattern</td>
</tr>
<tr>
<td></td>
<td>Cavity design;</td>
<td>constraint-based modeling using a B-rep model.</td>
<td>depends upon designer’s experience.</td>
</tr>
<tr>
<td></td>
<td>Cavity layout design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wu et al.[34]</td>
<td>Number of cavities;</td>
<td>Rule-based approach; Use of parametric</td>
<td>User selects the layout pattern; Clearances details are</td>
</tr>
<tr>
<td></td>
<td>Cavity design;</td>
<td>design to store pre-constructed gating elements.</td>
<td>not considered.</td>
</tr>
<tr>
<td></td>
<td>Cavity layout design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lee and Lee [35]</td>
<td>Cavity design</td>
<td>Rule-based approach.</td>
<td>System is not able to calculate draft for different types of walls.</td>
</tr>
<tr>
<td>Yan et al.[36]</td>
<td>Cavity design</td>
<td>Control point translation method.</td>
<td>Type of wall (i.e., outside, inside and hole) factor, is</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>not accounted in draft allowance determination.</td>
</tr>
<tr>
<td>Author</td>
<td>Issues Address</td>
<td>Methodology</td>
<td>Limitations</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Ye et al.[37]</td>
<td>Number of cavities; Cavity layout design</td>
<td>Use of empirical relations; feature recognition technique for gate location and undercut identification.</td>
<td>Selection of cavity layout requires technical know-how; Clearances details are not considered.</td>
</tr>
<tr>
<td>Low and Lee [39]</td>
<td>Cavity layout design</td>
<td>Use of standard template for controlling geometrical parameters.</td>
<td>Cannot handle complex non-standard configurations; Lacks decision capabilities.</td>
</tr>
<tr>
<td>Low and Lee [40, 41]</td>
<td>Number of cavities; Cavity layout design</td>
<td>Rules and heuristics; Standard database and templates.</td>
<td>Number of cavities is taken as user input; Clearances details are not considered.</td>
</tr>
<tr>
<td>Hu and Masood[42]</td>
<td>Cavity layout design</td>
<td>Knowledge-based and object-oriented approaches; Uses case-based and rule-based reasoning.</td>
<td>System cannot extract the information from part product model; User inputs the number of cavities.</td>
</tr>
<tr>
<td>Dewhurst and Blum [43]</td>
<td>Number of cavities</td>
<td>Optimization based on processing time and die manufacturing cost.</td>
<td>Part geometrical limitations and delivery date are not considered.</td>
</tr>
<tr>
<td>Madan et al. [44]</td>
<td>Number of cavities</td>
<td>Knowledge-based approach.</td>
<td>Determination of number of cavities based on delivery date is not considered.</td>
</tr>
</tbody>
</table>
2.2 Core, Cavity and Side-Core Design

This section discusses previous research attempts on computer-aided design of core, cavity and side-core for multi-cavity dies, in sections 2.2.1 and 2.2.2 respectively.

2.2.1 Core and cavity design

Previous research attempts on the computer-aided design of core and cavity blocks for multi-cavity dies are discussed in following paragraphs.

Fu et al. [45] proposed a methodology to generate parting surface and core and cavity blocks for an injection moulding die. The parting line edges are classified into inner and outer edge-loops. The parting surfaces are generated by extruding the parting line edges to the boundary of the core and cavity bounding box. Boolean regularized difference operation (BRDO) method is used to generate core and cavity blocks. However, design of side-cores for undercut features has not been addressed in their work.

Hui and Tan [46] used sweep method to form core and cavity blocks of an injection moulding die. The part model is swept in the parting direction to generate a swept solid. A cavity preform is then generated between the cavity solid and the swept solid on the cavity side by using Boolean regularized difference operation (BRDO) method. A core preform is also created using a similar method. Finally, CAD models of the core and cavity blocks are generated. However, the proposed method is limited to parts, which do not have any through holes.
Shin and Lee [47] proposed a method which uses Euler based approach (EBA\textsuperscript{1}) to generate CAD model of the side-core and corresponding core and cavity blocks. In EBA, the Euler operation is the key process to generate the core and cavity block surfaces [9, 11, 45]. The parting surface is generated by extruding the parting line to split the mould cavity into two halves. However, this method is limited to parts that do not have through holes.

Zhou et al. [48] presented a feature based approach for automatic generation of an injection moulding die. The features of a part are first recognized using a universal hint-based feature recognition algorithm. The optimal parting direction is determined based on the feature model of the part. The core and cavity are automatically generated by splitting the bounding box of the part with the generated parting surface. However, the developed system is not able to handle parts with complex features, free-from surfaces, and real undercut features.

Priydarshi and Gupta [49] developed a system for automating the design of a multi-piece permanent mould. It determines accessibility of every facet along the chosen parting direction, by checking the obstruction of each facet with rest of the part facets. However, it approximates the free-form surfaces with a number of planar surfaces and therefore may result in loss of data of the part CAD model. The system is not suitable for a normal die-casting die, which uses two pieces, i.e., core and cavity.

\textsuperscript{1}Euler operations are used to create, manipulate and edit the faces, edges and vertices of a boundary model as the Boolean operations create, manipulate and edit primitives of CSG (Constructive Solid Geometry) models. Euler operators, as Boolean operators, ensure the integrity (closeness, no dangling faces or edges, etc.) of boundary models. They offer a mechanism to check the validity of these models. Some sample Euler operators are; make, kill, split, join, face, shell, etc. A linear combination of some primitive operators is capable of representing any admissible transitions, for instance, the name \textit{mev} stands for "make edge and vertex".
2.2.2 Side-core design

Previous research attempts on side-core design are discussed in the following paragraphs.

**Hui and Tan** [46] used the concepts of visibility and accessibility for demouldability analysis of a part model. Their method uses semi-infinite rays, originating from surface grid points towards a chosen parting direction to find accessibility of a surface. They used blocking factor to determine the extent of blockage along a chosen parting direction. All chosen directions are checked for the extent of blockage, and the direction having minimum blockage factor is chosen as final direction for side-core withdrawal.

**Shin and Lee** [47] developed a methodology for design of side-cores for an injection moulding die. It first detects all interference faces from the cavity and core by using a projection algorithm, and then generates the side-cores. However, this method can generate ambiguous results, when two or more undercuts overlap in the same plane.

**Zhang et al.** [50] reported an algorithm to automatically generate side-cores for an injection moulding die. The algorithm uses B-rep model of the part to: (i) identify the undercut edges, (ii) determine the undercut faces, and (iii) classify them to form individual undercuts. The algorithm groups all the external edges of a face as an outer loop, and all the internal edges of the face as an inner loop. However, the algorithm would face difficulties if an undercut edge does not belong to an inner or outer loop of a part face.

**Ye et al.** [51, 52] developed a hybrid method (graph-based combined with hint-based) to recognize the interacting undercut features by searching the cut-set of the undercut sub-graph. The face and edge properties are used as hints to recognize the
interacting features. Later, they extended their approach [51] by using extended attributed face-edge graph (EAFEG) representation to recognize interactive undercuts and generate side-cores. The EAFEG is based on topological relationship of a moulded part’s B-rep model. After recognizing undercut features, a Boolean operation is used to generate the side-core for each undercut. However, their work does not consider intersecting features which are usually present in the moulded parts.

**Banerjee and Gupta** [53] developed an algorithm to automatically generate the side-cores by using stereo lithography (STL) file of a part model. The candidate retraction space for each undercut facet is computed by determining the collision-free translation space. The side-core is considered to be retracted in a plane perpendicular to the mould opening direction. However, the algorithm gives an optimal solution only if each connected undercut region of the part requires three or fewer side-cores.

**Fu** [54] introduced the concepts of surface mouldability for identifying all the surfaces of the core, cavity and side-cores. The mouldability of undercut feature is analyzed and the features are grouped. The head geometry of the side-core is constructed by sewing all extracted undercut feature surfaces. The entire side-core is generated by uniting the side-core head with the side-core body. However, intersecting features, which are usually present in the moulded parts, are not considered.

**Bassi et al.** [55] developed an automatic feature recognition system for side-core design, which takes the part B-rep information along-with a specified parting direction as user inputs. The intersecting features of the part are identified by doing accessibility analysis. The system applies sweeping and regularized Boolean operations to analyze all
types of surfaces, including the free-form ones. However, the system cannot recognize the protrusion features with concave edges.

A summary of the literature on core, cavity and side-core design for multi-cavity dies is presented in Table 2.2.

### 2.3 Gating System Design

Previous research attempts on computer-aided design of gating system for die-casting dies are discussed in this section. Some of the research attempts [37, 56-63] related to computer-aided design of gating system for injection moulding dies provide a good insight into the concept, are also discussed, but are not directly applicable due to higher complexity of the die-casting process.

Singh et al. [64] proposed a system for gating system design for die-casting dies. It takes CAD file of die-casting part as input and uses process knowledge to determine different gating system parameters. It uses a feature library together with parametric design to generate CAD model of the gating system components. However, the system application is limited because it: (i) does not consider the location of undercut features, (ii) selects the gating elements manually, (iii) does not have all types of gates and runners available in the feature library, and (iv) is applicable to single cavity die-casting dies only.

Wu et al. [34] proposed a system for gating design, based on Unigraphics platform and uses its API. The system is composed of system databases, design modules and design evaluation module. The developed system helps in design of the gating elements. Parametric solid models of gating elements are pre-constructed and stored in the system database.
Table 2.2: Summary of the literature review on core, cavity and side-core design

<table>
<thead>
<tr>
<th>Author</th>
<th>Issue Address</th>
<th>Methodology</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fu et al.[45]</td>
<td>Core, cavity and side-core design</td>
<td>Feature recognition; BRDO method.</td>
<td>Parts with undercut features are not addressed.</td>
</tr>
<tr>
<td>Hui and Tan [46]</td>
<td>Core, cavity and side-core design</td>
<td>Feature recognition using V-map; Sweep method.</td>
<td>Limited to parts which do not have any through holes.</td>
</tr>
<tr>
<td>Shin and Lee [47]</td>
<td>Core, cavity and side-core design</td>
<td>Euler based approach (EBA).</td>
<td>Generates ambiguous results when undercuts overlap in same plane.</td>
</tr>
<tr>
<td>Zhou et al.[48]</td>
<td>Core and cavity design</td>
<td>Feature based approach.</td>
<td>Not able to handle parts with complex features and free-from surfaces.</td>
</tr>
<tr>
<td>Priydarshi and Gupta [49]</td>
<td>Core and cavity design</td>
<td>Accessibility approach for feature recognition.</td>
<td>System approximates free-form surfaces into number of planar surfaces, which leads to loss of data of the part CAD model.</td>
</tr>
<tr>
<td>Zhang et al.[50]</td>
<td>Side-core design</td>
<td>Feature recognition algorithm; B-rep of a solid model.</td>
<td>Algorithm would face difficulties if an undercut edge does not belong to any inner or outer loop of the part faces.</td>
</tr>
<tr>
<td>Banerjee and Gupta [53]</td>
<td>Side-core design</td>
<td>Feature recognition using STL file.</td>
<td>System provides an optimal solution only if each connected undercut region of the part requires three or fewer side-cores.</td>
</tr>
<tr>
<td>Fu [54]</td>
<td>Side-core design</td>
<td>Surface mouldability technique for feature recognition.</td>
<td>Does not consider intersecting features.</td>
</tr>
<tr>
<td>Bassi et al.[55]</td>
<td>Side-core design</td>
<td>Feature recognition from the part B-rep model; accessibility analysis.</td>
<td>Cannot recognize protrusion features with concave edges due to their intersection with other features.</td>
</tr>
</tbody>
</table>
These parametric models can be retrieved from the database, and their design can be modified. After the desired parameters and locations of the gating elements are specified, these are joined with the cavity using Boolean operations. However, the system cannot handle complex parts and those with undercut features.

**Woon and Lee** [33] developed a die-design system using the commercial SolidWorks CAD software [13] and its API. The system comprises seven distinct modules. The gating system constructor module assists the die designer in insertion of gates, designing of runners, and placement of overflows. However, it does not address the design of gating elements. The selection of type of gate and runner is not automatic and requires an experienced designer.

**Yue et al.** [65] developed a system for design, analysis and manufacturing of die-casting dies for aluminum and magnesium alloys using Pro/Engineer [14] and Magmasoft [66] software. The design of gating elements is carried out manually using empirical relations. However, the system does not address determination of gating parameters, and selection of gating elements needs an experienced designer.

**Lin and Tai** [67-70] presented a system which uses simulated annealing (SA) optimization technique along-with a performance index to find optimal position of gate on free-form surface of a part. However, the system does not determine the gate parameters.

**Wu et al.** [71] developed a semi-automated approach for designing gating system of a die-casting die using P-Q² technique and feature-based parametric design, which is built on Unigraphics [16] platform. The system has a user-defined gating feature library for easy retrieval and placing. However, the system only considers three types of gates, two
types of overflow wells and four types of runner layouts. Furthermore, the system is limited
to four-cavity layouts only, and the user needs to select type of gating elements, and its
dimensions and position for placement.

**Choi et al.** [32] developed an automated system for design of the gate and runner
system for die-casting die. The system is developed on AutoCAD [72] platform, and
addresses the issues of gate design, runner design, and overflow design. However, the
system has some limitations, such as (i) application to single cavity layout only, (ii) does
not consider the undercut features, and (ii) requires human expertise.

**Fuh et al.** [12] developed a prototype system for die-casting die-design, which uses
API of Unigraphics [16] software. The system has functional modules, namely data
initialization, cavity layout, and gating system design. It uses P-Q^2^ approach to select the
initial process parameters. However, selection of gating elements is done by the user.

**Reddy et al.** [30] developed a software that provides intelligent assistance in
several tasks involved in the design of die-casting dies. The tasks include material
selection, parting line location, gating design calculations, and die layout design. The
gating design module calculates the gating dimensions. The system is however limited to
axis-symmetric components only.

**Zhang et al.** [73] presented a die-casting die-design system which can determine
the location, shape and dimensions of the gating elements. It uses P-Q^2^ technique to check
the suitability of the die according to process parameters. However, it does not help in
CAD model generation of gating elements.
**Hu et al.** [74] developed a system to design and optimize runner and gating elements for a hot chamber magnesium die-casting die using Magmasoft [66] software. The runner and gating elements are optimized on the basis of visual analysis of the filling pattern of the metal. However, it does not consider multi-cavity dies.

**CastView** [75] is a die-design visualization tool, developed by NADCA [76], that presents die-casting specific information in a 3-dimensional graphical form. The tool is useful to determine parameters of the gating systems in accordance with NADCA’s recommendations. Another goal of the software is that it keeps track of the complicated design of gating elements.

**DiEdifice** [77] is a die-casting die-design software that focuses on the design of gate, runner and overflow. It takes STL file of the part model as input and determines dimensions of the gating elements. Lastly, solid model of the gate, runner and overflow is generated based on the user provided information. However, the user is required to decide placement of the gating system in the die, which decision is not automatic and requires human expertise.

**CASTFLOW** [78] assists the designer to develop the gating system that matches the metal pumping capacity of a die-casting machine. It matches the gating system parameters with the metal flow pressure and speed requirements of a pressure die-casting die. After taking required input from the user, the software determines dimensions of the gating system elements and performs fill analysis to check the metal flow pattern.

**Cast-Designer** [79] assists the designer to develop a gating system of a die for the pressure die-casting process. It helps the designer to start the gating system design from the
conceptual stage, followed by the parametric design stage, and lastly the tolerance control stage.

**DC-CALC** [80] software helps the user to calculate all the vital parameters of a die-casting die. The software can quickly analyze many die-machine combinations to find a feasible alternative. It shows the effect of change in gate depth on gate velocity and cavity fill time. It also shows the effect on surface quality of the part when the die temperature changes. The software displays a new $P-Q^2$ diagram every time a change is made by the user.

A summary of the literature on gating system design for multi-cavity dies is presented in Table 2.3.

## 2.4 Computer-Aided Die-Design Systems

This section discusses available computer-aided systems for die-casting die-design. Some relevant systems for the injection moulding die-design are also discussed.

**Reddy et al.** [30] developed a computer-aided design system that provides intelligent assistance in several tasks involved in the design of die-casting dies. These tasks include material selection, shrinkage allowance calculation, provision of draft allowance to the component, parting line location, determine gating parameters, and design cavity layout. The system considers the factors of maximum projected area, section thickness, and draw distance to generation the parting line. The databases of material and machines assist the designer to determine the number of cavities, alternative cavity layout, and gate dimensions.
<table>
<thead>
<tr>
<th>Author</th>
<th>Issue Address</th>
<th>Methodology</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singh <em>et al.</em> [64]</td>
<td>Design of gating system</td>
<td>Use of empirical relations; Process knowledge-base; Parametric feature library.</td>
<td>Limited to single cavity die-casting dies; Limited feature library; Does not consider undercut features.</td>
</tr>
<tr>
<td>Wu <em>et al.</em> [34]</td>
<td>Automatic generation of gating system elements</td>
<td>Parametric design using user defined function of Unigraphics; Gating elements design database and P-Q^2 technique.</td>
<td>Does not generate gating parameters; Limited to FAN type gate only.</td>
</tr>
<tr>
<td>Woon and Lee [33]</td>
<td>Die-design system for die-casting; Gating system design</td>
<td>SolidWorks API; Gating system design deals with the number of cavities and their layout, gate, runner and overflow design.</td>
<td>Gating parameters are not system generated; Gating system design is manual.</td>
</tr>
<tr>
<td>Yue <em>et al.</em> [65]</td>
<td>Gating system, overflows and cooling channels design</td>
<td>Use of empirical relations; Manual design of gating system in Pro/E.</td>
<td>Does not generate gating parameters; Gating system design is manual.</td>
</tr>
<tr>
<td>Lin and Tai [67-70]</td>
<td>Optimal gate location for freeform surface dies</td>
<td>SA optimization algorithm; Optimize gate location based on minimum wrap.</td>
<td>Does not generate gating parameters.</td>
</tr>
<tr>
<td>Wu <em>et al.</em> [71]</td>
<td>Design of gating system</td>
<td>P-Q^2 technique; Feature-based parametric approach; Gating system library.</td>
<td>Manual selection of gate type and its location; Does not generate gating parameters.</td>
</tr>
<tr>
<td>Fuh <em>et al.</em> [12]</td>
<td>Design of gating system</td>
<td>P-Q^2 technique; Feature-based parametric approach; Gating system library.</td>
<td>System does not generate gating parameters.</td>
</tr>
<tr>
<td>Zhang <em>et al.</em> [73]</td>
<td>Runner and gating system design</td>
<td>P-Q^2 technique; Filling simulation.</td>
<td>Does not generate gating parameters.</td>
</tr>
<tr>
<td>Gating design software [75, 77-80]</td>
<td>Design of gating system</td>
<td>P-Q^2 technique; Rule-based approach; Parametric design; Gating database.</td>
<td>Does not generate CAD model of gating elements; Manual assembly of gating elements.</td>
</tr>
</tbody>
</table>
The system architecture is modular and integrated with AutoCAD software [72] for display and editing purpose. However, the system can handle only axis-symmetric shape components, and considers only circular type layout pattern.

**Fuh et al.** [12] developed a system named *DieWizard* that provides several die-casting die-design functional modules as add-on application of Unigraphics software [16]. The data initialization module assists the user to load a die-casting part product model, input process data, and specify the die-opening direction. The layout design module determines the number of cavities and their layout in the selected die-base; the number of cavities is determined based on the selected machine information. However, selection of the layout pattern for the cavity requires human expertise. The system uses feature-based parametric approach to generate the gating elements. The parting design module is used to patch through holes, create parting line interactively, and generate core-cavity blocks. However, the system has the limitations that the: (i) parting design is limited to single-cavity die, (ii) side-core design is not considered, and (iii) the gating parameters are not determined.

**Choi et al.** [32] developed a system for automation of die-casting die-design activities, which specially focuses on the design of the gate and runner. The system is programmed in AutoLISP using AutoCAD platform [72]. As shown in Figure 2.2, the die-design activities are roughly composed of cast design (read as part design), die layout design and die generation. Firstly, the part file is input in the initial graphics exchange specification (IGES) format. The gating parameters are determined following the rule base. Thereafter, the gating system is assembled with the cast, and the die is generated. The
developed system is limited to single-cavity dies and does not consider undercut features. Furthermore, the system is only applicable to simple shapes, such as a cap-shape.

![Flowchart of the die-design system for die-casting developed by Choi et al. [32]](image)

**Fig. 2.2**: Flowchart of the die-design system for die-casting developed by Choi et al. [32]

**Woon and Lee** [33] developed a computer-aided system named *DiWorks* for die-casting die-design, which uses application programming interface (API) of SolidWorks CAD software [81]. The system consists of seven modules, which are shown in Figure 2.3. It helps to generate CAD model of a die-casting die from part product model of a die-cast part. The methodology used in the system combines feature-based and constraint-based modeling, and, geometrical and topological information extraction from a boundary representation (B-rep) part model. However, determination of the number of cavities, layout pattern and cavity layout are not automatic. Furthermore, selection of the gating elements and determination of their parameters need to be done interactively by the user.
Chan et al. [31] developed an interactive knowledge-based injection moulding die-design system called IKB-MOULD, which uses part design and die manufacturing knowledge. It provides an interactive environment to assist the designers in rapid completion of the die-design. The system is divided into product model interface, die-design module, knowledge-base and some other libraries. The die-design module of the system is divided into the following three processes:
• The pre-mould process caters to the shrinkage and draft requirements of the product, which are based on the selected material.

• The initial die-design process selects the die base, the number of cavities, and layout of the cavities.

• The detailed die-design process facilitates assembly, manufacturing, 2-D drawing, and bill of material (BOM).

However, the system does not consider geometrical constraints for calculating the number of cavities. Furthermore, the system lacks in the level of automation, and considers the balanced cavity layout patterns only.

Mok et al. [62] developed an interactive knowledge-based system named IKMOULD for the injection moulding die-design. The system is developed on Unigraphics [16] platform using ‘C’ programming language [82, 83]. The system has three modules, namely the computational module, the knowledge-based module, and the graphics module. The system uses a rule based approach to determine the cavity layout pattern, along-with a knowledge-base that can be accessed by the die designer. The system allows the die designer to interactively enrich the knowledge-base of the system. Mok et al. [84] further modified the system by incorporating internet capability for knowledge acquisition. However, the limitations of both of the system remain the same, such as: (i) the number of cavities is entered manually, (ii) design of cavity layout requires designer experience, and (iii) the gating parameters are not determined.

A summary of the literature on computer-aided die-design systems is presented in Table 2.4.
### Table 2.4: Summary of literature on computer-aided die-design system

<table>
<thead>
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<th>Author</th>
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<th>Methodology</th>
<th>Limitations</th>
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<tbody>
<tr>
<td>Reddy et al.[30]</td>
<td>Die-casting die-design</td>
<td>Rule based approach; Use of machine, material, and knowledge database.</td>
<td>Can handle axis-symmetric shape components; Limited to circular type layout pattern.</td>
</tr>
<tr>
<td>Fuh et al.[12]</td>
<td>Die-casting die-design</td>
<td>Unigraphics API; P-Q^2 Technique; Feature-based parametric approach; Gating library.</td>
<td>Number of cavities is determined based upon the selected machine only; Limited to single-cavity die; Side-core design is not considered; Does not generate gating parameters.</td>
</tr>
<tr>
<td>Choi et al.[32]</td>
<td>Die-casting die-design</td>
<td>Rule based approach; Gating database.</td>
<td>Limited to single-cavity die; Does not consider undercut features; Most of the actions are not system supported.</td>
</tr>
<tr>
<td>Woon and Lee[33]</td>
<td>Die-casting die-design</td>
<td>SolidWorks API; Feature-based and constraint-based modeling using a B-rep model.</td>
<td>Determination of number of cavities, layout pattern and cavity layout requires human expertise; Selection of type of gating elements and their sizes are not system supported.</td>
</tr>
<tr>
<td>Chan et al.[31]</td>
<td>Injection moulding die-design</td>
<td>Rule based approach; Knowledge-based system with help of some other libraries.</td>
<td>Number of cavities is determined using empirical relations only; Geometrical constraints of part model are not considered to calculate the number of cavities.</td>
</tr>
<tr>
<td>Mok et al.[62, 84]</td>
<td>Injection moulding die-design</td>
<td>Rule based approach; Interactive knowledge-based and internet based CAD system.</td>
<td>Number of cavities is entered manually; Design of cavity layout requires designer experience; Gating parameters are not determined.</td>
</tr>
<tr>
<td>Die-design module of CAD Software [13-16]</td>
<td>Die-casting die-design; Injection moulding die-design</td>
<td>Feature-based parametric approach.</td>
<td>Focus on few steps of die-design process; Lack of automation; Requires designer experience.</td>
</tr>
</tbody>
</table>
2.5 Research Gaps and Objectives of the Thesis

In this section, shortcomings of the previous research are discussed, which is followed by objectives of the thesis.

2.5.1 Shortcomings of the previous research

One of the shortcomings of the available systems [34-36, 39-42, 45-55] is that they address one or a few steps of the die-design process in an isolated manner. Most of the research papers are related to the injection moulding die-design, whereas a few papers [12, 24, 30, 32-34, 44, 64, 65, 67-71, 73, 74] address die-casting die-design. Furthermore, in the developed systems [12, 30-33, 62, 84] lack of data integration from the part design to the die-design stage is observed. Most of the die-casting die-design systems pertain to single-cavity dies only and multi-cavity die-casting dies have got less attention. In the following paragraphs, shortcomings of the literature reviewed at four stages of the die-design process, namely cavity layout design, core, cavity and side-core design, gating system design, and computer-aided die-design system are discussed.

2.5.1.1 Cavity layout design

As discussed earlier, cavity layout design has two stages; cavity design and layout design, shortcoming for both the stages are discussed here.

Cavity design

Lack of automation in the cavity design is observed in most of the available die-design systems. A designer has to spend much time and effort to decide about the shrinkage and draft allowances. The fact is that these allowances are dependent on factors, such as part material, and geometric features, which make this decision data dependent involving lot of computations. For example, determination of draft allowance depends on the type of wall, which may be internal, external or a hole. The height of
wall also has an effect on the draft allowance. To save time and effort of the die-designer, automation of the cavity design decision is required. This means that the shrinkage and draft allowance should be decided by the system based on the information extracted from the die-cast part model, material properties, needed knowledge-base, etc., with some information provided by the designer interactively.

Layout Design

There are two aspects worth consideration in the cavity layout design, first, determine optimal but feasible number of cavities, and second, arrange the cavities in a suitable manner in the die. The first decision to determine the number of cavities depends on many aspects, such as part cost, capability of the selected machine, delivery date of manufactured parts. Obviously, the decision is non-trivial and a designer has to spend much time and effort for it. Furthermore, available systems do not account for all the aspects to decide the number of cavities. Second, the arrangement of cavities in the die means: (i) selection of the suitable layout pattern, such as circular or rectangular, and (ii) placing the cavities in the die. These decisions also require information, such as amount of clearances between the cavities. Making such decisions manually is cumbersome and time consuming. A system is therefore required which can help decide the number of cavities, and arrange the cavities in the die taking into account all important influencing factors.

2.5.1.2 Core, cavity and side-core design

Design of multi-cavity die-casting die is quite common in the industry, but not much attention has been given in the past to design a system, which is capable of designing such a die. The design of core, cavity and side-core of a die-casting die is non-trivial involving much time and efforts of the die designer. The time and effort required increases manifold in case of a multi-cavity die that needs side-core(s) as well.
Most of the available systems: (i) are not able to generate core, cavity and side-core in an automated manner, (ii) require die-designer’s knowledge and experience, and (iii) are unable to handle complex features and undercuts. To generate core, cavity and side-core(s), a user needs to perform a number of activities that include: (i) create parting line and surface, (ii) create solid model of the bounding box, (iii) split bounding box along parting surface, (iv) select side-core withdrawal direction, (v) create sketch to represent dimensions of the side-core, and (vi) perform Boolean operations to get core-cavity blocks and side-core. A system is therefore needed that should generate the core, cavity and side-core for multi-cavity dies in a semi-automated manner by minimizing the effort of the user.

2.5.1.3 Gating system design

Design of gating system encompasses several steps, involves complex computational work, and requires experience of the die-designer to get successful gating system. In case of a multi-cavity die-casting die, the complexity of the gating system design increases manifold. The industry utilizes a number of design guidelines for design of the gating system that are based on process requirements, industry best practices and published literature. These guidelines are not fully utilized in the available systems. Furthermore, the systems that can determine parameters of the gating system elements for a multi-cavity die, and use that information for generating their CAD models are lacking. Therefore, there is a need of a system that combines design knowledge and rules, and industry best practices along-with the data integration capabilities of a CAD system for the design of an effective gating system in a manner which is efficient in terms of time and efforts.
2.5.1.4 Computer-aided die-design system

As discussed earlier, many of the computer-aided design systems available today provide applications for die-design. These die-design modules of CAD systems are widely used to speed up product realization process for complex die-casting die-design process and to assist the die-designer in design revisions. CAD model of the part provides a basis for die-design. However, lack of data integration from part model to complete die-design is observed. Most of the computer-aided systems are limited to few die-design activities in an isolated manner and do not provide an integrated framework for complete die-design. The die-design knowledge and user input at various stages of die-design is still required. To develop a knowledge-based computer-aided system, which integrates most of the die-design activities taking CAD (or part product) model as input for design of a multi-cavity die-casting die would be highly beneficial for the die-designers and the die-casting industry.

After identifying gaps in the previous research, it is found that there is a need to develop a knowledge-based system which can address the issues related to design of a multi-cavity die-casting die. The system should take into account important factors, such as economic considerations, delivery time, part geometry and manufacturing resources, to decide the number of cavities and their layout, design the core, cavity and side-core, and design the gating system. Furthermore, the system must also have a good level of automation and minimal interference from the user to make decisions in the die-design process of a multi-cavity die-casting die. With increased use of CAD systems for die-casting die-design and manufacturing, developing a system based on the platform of a commonly used CAD system would provide the benefit of data integration.
2.5.2 Objectives of the thesis

Primary focus of the thesis is to develop a computer-aided system for multi-cavity die-casting dies. The objectives of the thesis, which are divided under four categories, namely cavity layout design, core-cavity and side-core design, gating system design, and computer-aided die-design system, are presented in following paragraphs.

2.5.2.1 Cavity layout design

The cavity layout design is carried out in two steps, which are below mentioned:

(i) Cavity design

- Determine shrinkage allowance using properties of the part material. Apply shrinkage allowance on all dimensions of the part CAD model in an automated fashion.

- Determine draft allowance taking into account the influencing factors, such as type of wall, wall height, and part material. Apply determined draft allowance for each wall in the part CAD model.

(ii) Layout Design

- Determine optimal but feasible number of cavities by accounting for influencing factors, namely delivery requirements, allowable production cost, specifications of the selected machine, and part geometric shape together. Determine layout pattern of the cavities taking into account the type of feeding system, namely bottom and central feeding system.

- Orient and place the cavities in the die by selecting a suitable die-base. Use die-design knowledge to decide the clearances required to accommodate the gating system, and side-cores. The selected die-base need to be from one of the standard sizes available.
2.5.2.2 Core, cavity and side-core design

- Generate CAD models of core and cavity blocks of a multi-cavity die-casting die in a semi-automated manner, with minimum user interaction.
- Generate CAD models of the side-core in the event of the part model having an undercut feature(s).

2.5.2.3 Gating system design

- Interactively provide information to the die-designer for basic design rules, guidelines, and industry best practices for design of gating system elements.
- Determine parameters of the gating system elements for a given part model in a semi-automated manner using established gating knowledge-base with some interaction from the user.
- Generate CAD model of the gating system elements for a multi-cavity die-casting die. Help the die-designer to place the gating system elements in the die by joining it with the existing arrangement of cavities.

2.5.2.4 Computer-aided die-design system

- Present an integrated framework of die-casting die-design that can handle multiple cavities also.
- Verify the integrated framework by conducting case studies on the die-cast parts taken from the industry.