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DEVELOPMENT OF AN EXPERT SYSTEM FOR THE DETERMINATION OF INJECTION MOULDING PARAMETERS OF THERMOPLASTICS

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ABSTRACT

DEVELOPMENT OF AN EXPERT SYSTEM FOR THE DETERMINATION OF INJECTION MOULDING PARAMETERS OF THERMOPLASTICS

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M.S. in Mechanical Engineering
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In this thesis, an Expert System (ES) called EX-PIMM is developed for the determination of injection moulding parameters of thermoplastic materials. The system has a modular structure, and it consists of three modules. The first module is used to select best Plastic Injection Moulding Machine(s) (PIMMs) for the given thermoplastic resin and defined part. The second module is used to select best thermoplastic resin(s) for the given PIMM and defined part. The last module can be considered as the combination of other modules. It is used for the determination of the optimum number of cavities for the given machine and material, and defined part. There are totally 623 PIMMs and 27 thermoplastics in the machine and material databases, respectively.

The primary objective of this research was to develop an interactive and modular expert system for shop-floor use that can be used by an average end-user (operator) and produce all feasible (acceptable) solutions to the end-user. For this purpose, all rules and facts related to the parameters of injection moulding process

have been acquired from experts and sources. After that, all these knowledge have been implemented at an expert system shell, called GoldWorks, to construct the Knowledge-Based Expert System (KB-ES). The developed system is able to interact with database files that are created in Lotus 1-2-3 database program to reach solutions.

The developed system has a modular structure. Each module has its own Knowledge Base (KB) which contains related rules and functions required to reach conclusions. During run-time, each module uses only its own KB. There are some miscellaneous KBs in the system. These files are used to load necessary tools into memory such as graphic interface, Lotus 1-2-3 interface, etc. All KBs were written in LISP language. Lotus 1-2-3 database files include several thermoplastic resins and PIMMs for the selection process. A special "award" system was also created for the PIMMs and thermoplastic resins which are satisfactory for the given job.

The developed system is an interactive one. In other words, the end-user can directly enter all necessary data to the developed system, and can also change some machine and/or material specifications during run-time of the system. Therefore, this provides end-users to customize the developed system and to make the system independent from the algorithm.

Keywords: Artificial Intelligence (AI), Expert System (ES), Injection Moulding, Thermoplastics, Plastic Injection Moulding Machine (PIMM).

ÖZET

TERMOPLASTİK MALZEMELERİN ENJEKSİYON KALIPLAMA PARAMETRELERİNİN GELİŞTİRİLEN BİR UZMAN SİSTEM İLE BELİRLENMESİ

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Bu tezde, termoplastik malzemelerin enjeksiyon kalıplanmasında kullanılan parametrelerin belirlenmesi için "EX-PIMM" olarak adlandırılan bir Uzman Sistem (ES) geliştirilmiştir. Geliştirilen sistem, modüler bir yapıya sahiptir ve üç modülden oluşmaktadır. Birinci modül, verilen bir termoplastik malzeme ve tanımlanan bir parça için en iyi Plastik Enjeksiyon Kalıplama Makinası (PEKM) yada makinalarının seçilmesi için kullanılır. İkinci modül, verilen bir PEKM ve tanımlanan bir parça için en iyi termoplastik malzeme yada malzemelerin seçilmesi için kullanılır. Üçüncü modül, diğer modüllerin kombinasyonu olarak düşünülebilir. Bu modül, verilen makina ve malzeme ile tanımlanan bir parça için en iyi kavite sayısının belirlenmesi için kullanılır.

Bu çalışmanın temel amacı, kabul edilebilir bütün sonuçları üretebilen, atelyede tezgah başında ortalama bir kullanıcı (operatör) tarafından kullanılabilecek, etkileşimli ve modüler bir uzman sistemin geliştirilmesidir. Bu amaçla, enjeksiyon kalıplama metodu ile ilgili parametrelere ait tüm kurallar ve bilgiler uzmanlardan ve kaynaklardan elde edilmiştir. Daha sonra; bütün bu bilgiler, kural-tabanlı uzman sistem oluşturmak üzere, Goldworks olarak bilinen uzman sistem kabuğunda kural haline getirilmiştir. Geliştirilen sistem, sonuçlara ulaşmak için, Lotus 1-2-3 veri-depolama programında oluşturulan veri dosyaları ile çalışabilmektedir.

Geliştirilen sistem, modüler bir yapıya sahiptir. Her modül, sonuçlara ulaşmak için gereken tüm kuralları ve fonksiyonları içeren, kendine ait Bilgi Tabanı (BT) dosyasına sahiptir. Çalışma esnasında, her modül sadece kendine ait BT dosyasını kullanır. Ayrıca, sistemde çeşitli BT dosyaları vardır. Bu dosyalar; grafik arayüz, Lotus 1-2-3 arayüzü, vb. gerekli araçların hafızaya yüklenmesi için kullanılır. Bütün BT dosyaları, LISP dilinde yazılmıştır. Lotus 1-2-3 veri dosyaları, seçme işlemi için gerekli birçok termoplastik malzeme ve PEKM'ler içermektedir. Verilen bir iş için başarılı olan PEKM'ler ve termoplastik malzemeler için de özel bir "ödül" sistemi yaratılmıştır.

Geliştirilen sistem aynı zamanda etkileşimlidir. Bir başka deyişle, kullanıcı; gerekli olan bütün veriyi direkt olarak sisteme girebilir, ve aynı zamanda, sistemin çalışması esnasında, bazı makina ve/veya malzeme özelliklerini değiştirebilir. Dolayısıyla bu, kullanıcıya, geliştirilen sistemi özelleştirme ve sistemi algoritmadan bağımsız yapma imkanı verir.

Anahtar Kelimeler: Yapay Zeka (YZ), Uzman Sistemler (US), Enjeksiyon Kalıplama, Termoplastik Malzemeler, Plastik Enjeksiyon Kalıplama Makinası (PEKM).

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LIST OF SYMBOLS

Name of Attribute	*Unit*	*Designation*
Shot weight (capacity) of machine	g	$S_{machine}$
Shot weight in terms of a resin	g	S_{resin}
Shot weight in terms of polystyrene (PS)	g	S_{PS}
Specific gravity of PS (at room and plast. temp.)	-	SG_{PS}
Specific gravity of resin at room temperature	-	SG_{resin}
Specific gravity of resin at plasticizing temperature	-	SG_{plast}
Density of resin	g/cm^3	ρ_{resin}
Mass of one preform (cavity)	g	$M_{preform}$
Optimum number of cavities	-	Q_{opt}
Number of cavities	-	Q
Projected cavity area	cm^2	$A_{preform}$
Clamping force (tonnage) of machine	tonnes	$CF_{machine}$
Clamping force capacity of resin	tonnes	CF_{resin}
Viscosity factor of resin	-	VF_{resin}
Maximum clamping force estimation	$tonne/cm^2$	CFE_{max}
Minimum clamping force estimation	$tonne/cm^2$	CFE_{min}
Screw diameter	cm	d_{screw}
Screw L/D ratio	-	LD
Injection pressure of resin	bar	IP_{resin}
Injection pressure capacity of machine	bar	$IP_{machine}$
Screw (injection) stroke	cm	SS
Injection stroke/screw diameter ratio	-	SD
Theoretical injection volume	cm^3	IV_{theo}
Actual (calculated) injection volume	cm^3	IV_{act}
Injection rate	cm^3/s	IR
Injection speed	cm/s	IS
Screw rotary speed	rpm	SRS
Screw surface speed	cm/s	SSS
Plasticizing capacity	g/s	PC

Cycle time	s	CT
Dry cycle time	s	DCT
Mould opening stroke	cm	MOS
Sprue length	cm	SL
Mass of moulded part	g	M_{part}
Volume of moulded part	cm^3	V_{part}
Projected are of moulded part	cm^2	A_{part}
Maximum mould height	cm	MH_{max}
Minimum mould height	cm	MH_{min}
Maximum (Platen) daylight	cm	PD
Space between tiebars (horizontal x vertical)	cm x cm	SBT_{hor} x SBT_{ver}
Electric motor rating (installed driving pump power)	kW	P_{pump}
Electric heater rating (heater power)	kW	P_{heater}
Total power	kW	P_{total}
Hopper capacity	g	HC

CHAPTER I

INTRODUCTION

1.1. INTRODUCTION

This chapter gives a brief introduction to the context of this study. Description of plastics technology, injection moulding process and process parameters are introduced in this chapter. Artificial Intelligence (AI) and Expert Systems (ESs) are also described briefly. Finally, the structure of the system developed in this work is discussed.

1.2. PLASTICS

In general, the term *plastic* is applied to all materials capable of being moulded or modeled. Products can be made from plastic resins rapidly with close dimensional tolerance and excellent surface finish. Often they replace metals when lightness in weight, moisture or corrosion resistance, and dielectric strength are factors to be considered.

On the other hand, the use of plastics is limited because of comparatively low strength, low heat resistance, low dimensional stability, and often high material costs. Compared with metals, they are softer, less ductile, and more sensitive to deformation under load and embrittlement at low temperature. Many plastics are flammable and may deteriorate in sunlight. Fortunately, plastics have a good combination of a variety of properties, rather than extremes of any single property.

Plastics may be broadly classified as *thermosetting* and *thermoplastic*. Thermosetting plastics are formed to shape with heat, with or without pressure, resulting in a product that is permanently hard. Processes used for thermosetting plastics include compression or transfer moulding, casting, and laminating. Also, some are used for making rigid or flexible foams.

Thermoplastic materials, however, undergo no chemical change in moulding and do not become permanently hard with the application of pressure and heat. They remain soft at elevated temperatures until they are hardened by cooling, and they may be remelted repeatedly by successive applications of heat. Thermoplastic materials are processed principally by injection or blow moulding, extrusion, and thermoforming.

1.3. DECRIPTION OF THE INJECTION MOULDING PROCESS

Injection moulding is one of the most important polymer processing operations in the plastic industry today. Due to its ability to produce complex shape plastic parts with good dimensional accuracy and very short cycle times, injection moulding has become one of the greatly preferred manufacturing processes.

Injection moulding is a process in which a hot polymer melt is forced to flow into an empty, cold cavity of desired shape and then allowed to solidify under a high holding pressure.

The injection moulding process is a cyclic process. The significant stages of the process in order are as follows:

1. **Filling Stage** (filling the cavity with hot polymer melt at injection temperature)
2. **Packing Stage** (after the cavity is filled, additional polymer melt is packed into the cavity at a higher pressure to compensate the expected shrinkage as the polymer solidifies)
3. **Cooling Stage** (after packing stage, the mould is cooled until the part is sufficiently rigid to be ejected)
4. **Ejection Stage** (finally, the mould is opened and the part is ejected, after which the mould is closed again to begin the next cycle)

The significant elements of a Plastic Injection Moulding Machine (PIMM) can be grouped into four categories:

- **Injection Unit** (the way in which melted material is plasticized, or softened, and forced into the mould)
- **Clamping Unit** (the system for opening the mould and closing it under pressure)
- **Mould or Cavity Unit** (the type of mould to be used)
- **Control Unit** (the unit for machine controls)

1.4. AI AND ESs

Artificial Intelligence (AI) is commonly defined as the effort to develop computer-based systems (both hardware and software) that behave as humans. Such systems would be able to learn natural languages, accomplish coordinated physical tasks (e.g., robotics), and emulate human expertise and decision making (expert systems). Such systems would also exhibit logic, reasoning, and intuition. AI has provided several techniques with applications in manufacturing, such as Fuzzy Logic (FL), Expert Systems (ESs), Artificial Neural Networks (ANNs) and Genetic Algorithms (GAs).

Since 1980s, ESs are one of the most developed branch of AI. An expert system is a software program that encodes the knowledge of experts, and uses techniques other than conventional computer languages to represent that knowledge.

Frequently, experts possess knowledge which is extremely valuable to a company, but which cannot be expressed easily in conventional computer programs. Their knowledge often relies on experience from past situations which is reapplied when necessary to deal with a similar situation. This knowledge is often represented in the form of rules or heuristics.

The model of an expert system consists of four main parts:

1. **User Interface** (enables the end-user to interact with the expert system)
2. **Knowledge Base** (contains the facts and heuristics of the particular problem to be solved. It is commonly constructed by IF-THEN rules or frames with series of questions)
3. **Inference Engine** (provides the reasoning ability that interprets the contents of the knowledge base. It is actually a program to reach solutions by using rules or heuristics included in the knowledge base file)
4. **Knowledge Acquisition Mechanism** (also known as "**Development Engine**". It is used for capturing human expertise and transforming them into the knowledge base)

Like conventional programs, expert systems usually perform relatively well-defined tasks. Unlike conventional programs, expert systems also explain their actions, justify their conclusions, and provide end users with details of the knowledge they contain. An expert system may be easier to debug and modify than a traditional program performing the same task, because the knowledge is separated from the algorithms and is readily accessible at run time.

1.5. INJECTION MOULDING PARAMETERS

Determination of injection moulding parameters is a very complex task. In addition, it is not easy to handle the relationships between these parameters in order to obtain an effective and rapid moulding.

Buying a Plastic Injection Moulding Machine (PIMM) is not a small investment. Too much machine for the job at hand is wasteful; too little machine does not get the job done. Consequently, a sufficient machine knowledge is also needed to use the best PIMM in order to match the needs of the job. In addition, selection of the best thermoplastic material among several resins for the required process is a sophisticated task. Therefore, a great experience is also required about material science. The combination of these two tasks also gives the optimum number of cavities.

There are several attributes in the determination of the best PIMM and the best thermoplastic resin. These attributes are classified into quantifiable attributes, on-off attributes, and non-quantifiable attributes. The first two types could be obtained from the specification and description of the machine, the last type could only be determined by user's measurement, usage or his/her expertise.

1.6. OBJECTIVES OF THE WORK

The main objective of this study is to develop a modular expert system for the determination of the optimum injection moulding parameters by means of material and machine databases. The purpose of this work is to obtain rules and facts related to the determination of injection moulding parameters, and implement them into a modular, interactive expert system shell to reach solutions.

The developed system is called EX-PIMM (EXpert system for Plastic Injection Moulding Machines). The system consists of three modules:

1. Selection of the best PIMM(s).
2. Selection of the best thermoplastic resin(s).
3. Determination of optimum number of cavities.

The first two modules have similar algorithms. The objective of both modules are to select the best machine/material according to given material/machine specifications and defined part. Third module can be considered as the combination of first two modules. It is used for the determination of the optimum number of cavities with respect to the given machine and material specifications, and defined part.

Each module has its own knowledge base containing rules and facts. However, there is a simultaneous connection between them during run-time of the system. All necessary information can easily be read from other knowledge base files. The developed system is user-interactive providing an interactive environment to the end-user for supplying necessary information to the system. The results and decisions are written to database files for future use.

1.7. CONTENTS OF THE CHAPTERS

The brief contents of the chapters in this manuscript can be written as follows:

- **Chapter 2** is devoted to literature survey related to this study. The most related works related to the mould and process parameter design, and Artificial Intelligence (AI) applications of injection moulding are included in this chapter. Conclusions drawn from the current literature are also highlighted.

- **Chapter 3** introduces injection moulding process in detail. Detailed information about plastics, types of PIMMs and moulds, and auxiliary components used in the process are given in this chapter.

- **Chapter 4** provides a discussion on the definition of AI and a review on AI techniques. The definition and construction of Expert Systems (ESs) are also discussed in this chapter.

- **Chapter 5** explains the definition and use of the most significant injection moulding parameters in detail.

- **Chapter 6** concentrates on the description of the developed system. The modules of the EX-PIMM and their algorithms are illustrated step-by-step.

- **Chapter 7** gives an example for all modules of the developed system. Each module has a different example illustrating the stages in their algorithms.

- **Chapter 8** involves a discussion about the main issues of this study, capability of the developed system, and the conclusions obtained from this study. The recommendations for future works are also presented.

CHAPTER II

LITERATURE SURVEY

2.1. INTRODUCTION

This chapter represents a survey of the most related literature with the study reported in this thesis. Since injection moulding process is a very divergent and complex task, there are several studies on the design and/or optimization of injection moulding process. In addition, many works have been done on the design and/or optimization of moulds and moulded parts. Apart from these, process control of the injection moulding is another interest area of researchers about this subject. At the end of this chapter, conclusions drawn from the literature is reported.

2.2. LITERATURE ON *"MOULD AND PROCESS PARAMETER DESIGN"*

Optimization of flow in plastic injection moulding process has been studied by Seow and Lam [1]. One of the problems faced by designers when designing quality into a part is the process of cavity balancing. The software developed by using FORTRAN language is running by means of trial-and-error method to achieve an optimum flow during process.

The cooling time of the polymer melt in injection moulding is a major part of the total time of the processing cycle. Because of the significance of the rate of cooling to the economics of the process, the heat-transfer phenomena which occur in polymer cooling has revived considerable investigation in the literature. Research into the cooling time of polymers melts in injection moulding was reviewed by Liang and Ness [2].

Turng et al [3] have studied the optimization of moulding process at low injection pressures. With the use of commercial simulation software, strategies based on minimizing injection pressure and clamp force are developed for optimizing moulding of both thick and thin parts at high and low speeds. Thinner parts are shown to be naturally suited for high-speed filling, whereas thicker parts have a longer optimum fill time. In this study, an initial consideration of design pressure and processing optimizing strategies aimed at reducing injection pressure and clamp force have been presented.

Ari et al [4] proposed a systematic approach for solving an injection moulding problem. A corrective action plan is recommended to solve the short shot problem of the injection moulded parts from a technical and management aspect.

Automatic recognition and extraction of undercut features is a bottleneck in computer-aided injection mould design. Nee et al [5] proposed a methodology for the recognition and extraction of undercuts based on their geometrical characteristics and topological relationships of the moulded parts. With the developed software, undercuts can be classified and recognized automatically from a 3-D model of a moulded part. After all undercuts are extracted, the optimal parting direction is chosen based on the proposed criterion of considering the number of possible undercuts and their corresponding undercut volumes.

A CAD environment has been developed by Wang et al [6] to facilitate the ejector system design. In this study, an efficient algorithm for optimizing the arrangement and selection of ejectors was represented. In addition, a case study has been implemented in this study.

The runner-system design is of great importance to achieve a successful injection moulding process of family mould with multiple cavities. Li and Shen [7] presented a feasible means to optimize the runner design automatically by integrating optimization theory with a flow/thermo-simulation program.

A simple viscous flow model which decribes the behaviour during the filling stage was presented and implemented by Hill [8]. Of particular interest is the formation of a layer of solid plastic along the walls of the mould. In this study, both analytical and numerical investigations have been carried out.

2.3. LITERATURE ON *"ARTIFICIAL INTELLIGENCE AND CAD/CAM/CAE OF MOULDING"*

A study on numerical and experimental investigation of neural network-based intelligent control of moulding processes is presented by Demirci et al [9]. In this study, the current investigation is focused on the development of intelligent injection moulding processes by utilizing a neural network based control unit. The emphasis given in this study is on the control of flow front progression during injection moulding processes.

A cased-based reasoning system has been developed by Kwong et al [10] for determining proper moulding parameters. Cased-based reasoning views reasoning as a process of remembering one or a small set of concrete instances of cases and basing decisions on comparisons between the new situation and old one. This approach will not only allow experience of setting moulding parameters to be represented easily, it will also eliminate the knowledge elicitation bottleneck which is inherent in expert systems. In addition, a self-learning capability can be incorporated easily within the cased-based reasoning system.

An Artificial Intelligence System (AIS) for obtaining the magnitude of process parameters in plastic injection moulding operation has been developed by Shelesh-Nezhad and Siores [11]. The system is user interactive and can be used at shop floor. This system applies two techniques: Rule-Based and Case-Based Reasoning. Case-Based Reasoning is used to derive the first trial setting of processing parameters, while the Rule-Based sub-system suggests a set of corrective actions to deal with possible corresponding variations in moulding. The system reduces optimization time and human expert dependency.

A framework for knowledge-based evaluation of the conceptual design development of injection moulding parts has been developed by Chin and Wong [12]. This prototype knowledge-based system is capable of selecting the appropriate plastic material and generate the major injection mould design features.

A prototype expert system for injection-moulded plastic parts has been developed by Steadman and Pell [13] to demonstrate the utility of expert systems for design applications. The prototype was implemented in an object-oriented, rule-based environment, and incorporates solid modeling software and external material databases.

Lim et al [14] developed a knowledge-based process planning system interfaced with design for injection mould. In this system, decision making of process design is performed by rules which were acquired from experienced process planners through interviews, and machining operation time is estimated by using emprical formulas derived from the actual shop floor data.

Zhongsuang et al [15] have developed an integrated CAD/CAE/CAM system for injection moulding. At the CAD/CAE stage, the drawings of injection moulded parts can be transformed into the drawings of the mould parts interactively and, according to the user's needs, the mechanical check, runner balance analysis, flow simulation and cooling simulation can be carried out. NC tapes for wire cutting or milling machine tools can be generated at the CAM stage.

The process paramaters of injection moulding have been set by human operators based on their experience iteratively. Even with the sophisticated CAE software tools, at present time, the interpretation of the analysis results and the subsequent process parameter adjustment are being done based on the human expertise. A learning system for the optimization of process parameters of injection moulding with neural network application in a process simulation environment has been developed by Choi et al [16]. This system generates an optimum set of process paramaters at the design stage with a minimum number of CAE simulation runs.

A framework of a concurrent process planning system for mould manufacturing has been developed by Lee et al [17]. A research on the development of a computer-based framework that supports concurrent mould manufacturing process planning was presented in this study. The results of this research facilitate the rationalization and automation of the mould development process planning, thus improving the efficiency and quality; and also reducing the cost of moulding product and process development.

An intelligent on-line quality monitoring system has been developed by Kazmer et al [18]. The system is composed of an initial input utilizing flow simulation for product and process optimization, an expert system developed for defect elimination on the production floor, a design of experiments approach to verify process stability and model the quality dynamics which provides information to, and a continuous and automatic production quality monitor and controller.

2.4. CONCLUSION

As depicted above, plastic injection moulding process is a very sophisticated process. Therefore, many studies and works could be found in the literature. However, there are few works done on the process parameter selection and/or optimization in the literature. Most of studies are based on the optimization of unique parameter in the moulding process. Some researchers used Artificial Intelligence (AI) in the optimization and/or design of the process. Determination of process parameters by using an Expert System (ES) is almost unique in the literature up to now. In addition, in this study, material and machine databases having wide range of information about available thermoplastic materials and injection moulding machines are integrated within the expert system.

CHAPTER III

INJECTION MOULDING

3.1. INTRODUCTION

This chapter gives detailed information and discussion of the injection moulding process and related subjects. Section 3.2 gives a brief information about plastics and thermoplastic materials. Description of the injection moulding process is included in Section 3.3. Sections 3.4.1 and 3.4.2 describe a typical injection moulding machine and types of injection moulding machines, respectively. Section 3.5 discusses types of moulds and dies. Clamping and toggle systems are discussed in Section 3.6. Sections 3.7.1-3 give detailed information about runners, sprues and gates. Design criteria and commonly used types of runners, sprues and gates are also explained in these sections. Finally, some advantages and disadvantages of the process are given in Section 3.8.

3.2. PLASTICS AND THERMOPLASTIC MATERIALS

3.2.1. General Information About Plastics

Plastic can be defined as organic material containing molecules of high molecular weight and which can be moulded to shape by the application of pressure at moderately high temperature. Once moulded, they may retain their plasticity or they may become permanently hard or brittle. Some plastics, however, are compounded as liquid and proceed to set without the application of either heat or pressure.

Plastics consist of a very large, different class of materials numbering about fifteen thousand showing a wide range of properties and processing characteristics. Like other materials, plastics are identified differently, such as plastics, resins, polymers, elastomers, foams, reinforced plastics, and composites. The terms "plastics", "resins" and "polymers" are usually taken as synonymous. Although plastics are soft and mouldable, even approaching a liquid condition during manufacturing process, they are solid in their finished state. The term "plastics" is generally attached to polymeric materials because these materials are basically capable of being moulded or formed with permanent deformation.

Based on the type of chemical reaction (polymerization) that links the molecules together plastics are classified as either thermoplastics or thermosets. Table 3.1 shows the difference between properties of thermoset and thermoplastic materials. In addition to the main categories of thermoplastics and thermosets, thermoplastics can be further categorized into amorphous, semi-crystalline, or liquid crystalline materials, depending on the polymer chain conformation or morphology. Other classes include elastomers, copolymers, compounds, commodity resins, and engineering resins. Additives, fillers, and reinforcements are other classifications that relate directly to plastics' properties and performance.

Table 3.1. Comparison of Structures and Properties of Thermoplastics and Thermosets [19].

Material	Thermoplastics	Thermosets
Microstructures	Linear or branch molecules, no chemical bonds among the molecules.	Cross-linking network with chemical bonds among molecules after the chemical reaction.
Reaction to Heat	Can be re-softened (physical phase change).	Cannot be re-softened after cross-linking without degradation.
General Properties	Higher impact strength, easier processing, better adaptability to complex designs.	Greater mechanical strength, greater dimensional stability, better heat and moisture resistance.

3.2.2. Thermoplastics

Thermoplastics typically have high molecular weights resulting from a high degree of polymerization. The long molecular chain, either linear or branched, has side chains or groups that are not attached to other polymer molecules (as shown in Figure 3.1). As a result, thermoplastics can be repeatedly softened (or hardened) by an increase (or decrease) in temperature.

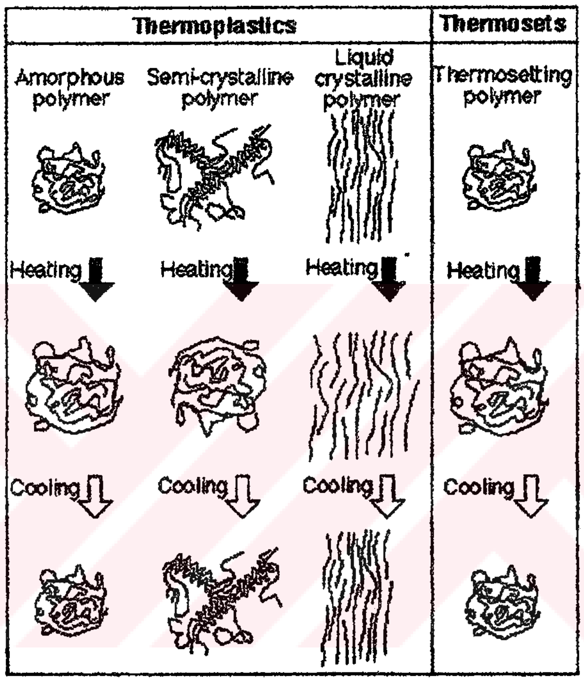

Figure 3.1. Microstructure of Various Plastics, and the Effect of Heating and Cooling During Processing.

Thermoplastics account for more than 70% of all polymers produced. Among thermoplastics, the commodity resins, for example, high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) account for more than 90% of all thermoplastics. On the other hand, the engineering resins, such as, acetal, acrylonitrile butadiene (ABS), nylon, polycarbonate (PC), etc., offer improved performance including higher mechanical properties, better heat resistance, higher impact strength. Thus, they are more expensive than the previous ones.

Thermoplastic materials are purchased as pellets or granules. They are melted by heat under pressure into a relatively viscous fluid and shaped into desirable product or form by cooling. Thermoplastics generally offer higher impact strength, easier processing, and better adaptability to complex designs than thermosets.

3.2.2.1. Amorphous Thermoplastics

Molten polymer molecules in an unstressed state are randomly oriented and mixed with other molecules. Amorphous materials retain this type of mixed and disordered molecular configurations regardless of their states. When the temperature of melt decreases, amorphous polymers start becoming rubbery. When the temperature is further reduced to below the glass transition temperature, the amorphous polymers turn into glassy materials. Amorphous polymers possess a wide softening range, moderate heat resistance, good impact resistance, and low shrinkage. Some typical application areas are appliances, business machine housings, lenses, medical equipment, electronic connectors, automotive instrument panels, lighting, and packaging.

3.2.2.2. Semi-Crystalline Thermoplastics

Crystalline materials are polymer chains that do not have bulky pendant groups, chain branches, or closs-links. They may accommodate themselves in a well-ordered regular lattice (polymer crystallite) when the molten polymers are cooled below the melting temperature. Such a crystallization process stops when the materials are cooled below the glass transition temperature. Since it is difficult to achieve 100% crystallization under normal processing conditions, any crystallizable polymers are typically semi-crystalline, possessing both amorphous and crystalline phases. The degree of crystallinity depends on both the chemical structure of the polymer and the processing conditions. Semi-crystalline polymers have a distinct melting point, good chemical and heat resistance, good lubricity, low moisture absorption, and high shrinkage. Some typical application areas are electrical parts, gears, door latches, bearing applications, films, chemical bottles, industrial trash bags, piping, household equipment casings, painted automotive exterior body components, integrated circuit carriers, food packaging, and beverage containers.

3.2.2.3. Liquid Crystalline Thermoplastics

Liquid crystalline polymers (LCPs) exhibit ordered molecular arrangements in both the melt and solid states. These materials are characterized by their stiff, rod-like molecules that form the parallel arrays or domains. LCPs offer a number of processing and performance advantages including low melt viscosity, low mould shrinkage, chemical and heat resistance, stiffness, creep resistance, and overall dimensional stability. Some typical application areas are electrical and electronic connectors, sockets, metal and ceramic replacements that require resistance to high temperatures, chemicals, mechanical stress and creep resistance, automotive and aerospace parts that require the ability to withstand high temperatures and flame retardance, and chemical-processing components that exist in aggressive environments.

Table 3.2. Comparison of Structures and Properties of Amorphous and Crystalline Polymers [19].

Material	Amorphous Polymers	Crystalline Polymers
Common Materials	Acrylonitrile butadiene styrene (ABS), Acrylics (e.g., PAN,PMMA), Polycarbonate (PC), Polystyrene (PS), Polyvinyl chloride (PVC), Styrene acrylonitrile (SAN)	Acetals, Nylon, Polyethylene (PE), Polypropylene (PP), Thermoplastic Polyesters (e.g., PBT, PET)
Microstructure	Random molecular orientation in both liquid and solid phases.	Random molecular orientation in liquid phase but densely packed crystallites occurs in solid phase.
Reaction to Heat	Solvents over a range of temperature (no apperent melting temperature).	Fairly distinct melting temperature.
General Properties	Transparent, poor chemical resistance, low volumetric shrinkage in moulding, generally low strength, generally high melt viscosity, lower heat content.	Translucent or opaque, excellent chemical resistance, high volumetric shrinkage in moulding, generally high strength, generally low melt viscosity, higher heat content (with heat of crystallization).

Table 3.2 lists a summary of relevant structures and properties of amorphous and crystalline polymers.

3.3. INJECTION MOULDING PROCESS

Injection moulding is one of the most-used method of producing plastic articles. Beginning in 1927 with the introduction of cellulose acetate moulding resin, the injection moulding-process has continually occupied a leading position as a mass-production technique. Injection moulders as a group annually convert more amount of resin into useful products and account for greater expenditures for machinery, moulds, and auxiliary equipment than any other segment of the industry.

Injection moulding is a cyclic process (see Figure 3.2 for the complete cycle). It consists of mainly three stages:

1. Filling stage
2. Postfilling (packing and cooling) stage
3. Mould open (ejection) stage

In the filling stage, molten polymer maintained at a uniform temperature inside the barrel of injection machine is forced to flow through the nozzle into the sprue under a constant flow rate or constant pressure. Then, the runner system delivers the melt from the sprue to the gates of the part cavity inside the mould.

At the end of the filling stage, injection machine supplies a constant holding pressure, during which additional polymer melt is packed into the cavity, to compensate for the expected shrinkage as the polymer solidifies (packing stage). This is followed by cooling the part until the temperature everywhere within the plastic melt drops below a certain specified value so that the part is sufficiently rigid to be ejected without any distortion (cooling stage). The combination of packing and cooling stages are known as postfilling stage.

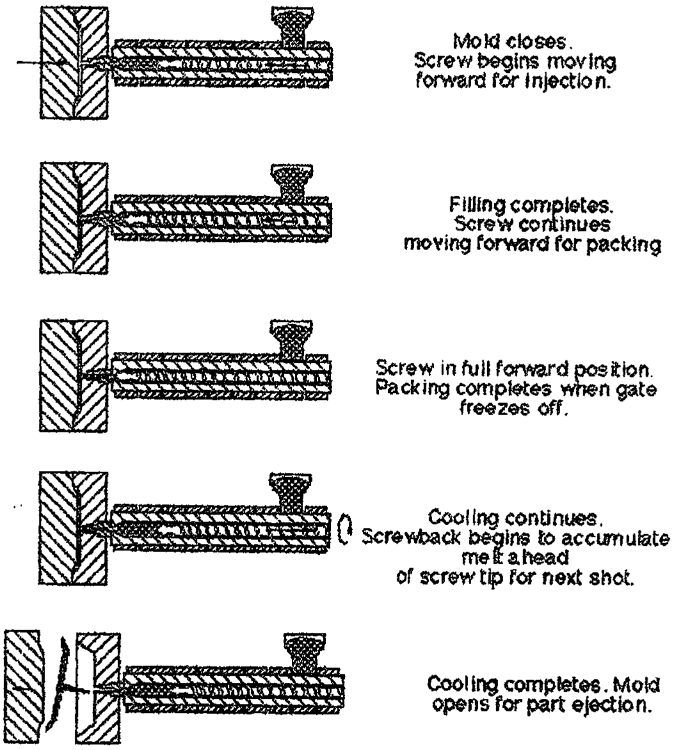

Figure 3.2. Typical Injection Moulding Cycle.

Finally, during the ejection stage, the mould is then opened and the part ejected, after which the mould is closed again to begin the next injection cycle.

3.4. PLASTIC INJECTION MOULDING MACHINE (PIMM)

For thermoplastics, the injection moulding machine converts granular or pelleted raw plastic material into final moulded parts via a melt, inject, pack, and cool cycle. Therefore, selection of the best machine among others is a great importance of mould designers and manufacturers.

3.4.1. Description of an Injection Moulding Machine

A typical injection moulding machine consists of following major components as shown in Figure 3.3:

1. Injection system
2. Hydraulic system
3. Mould system
4. Clamping system
5. Control system

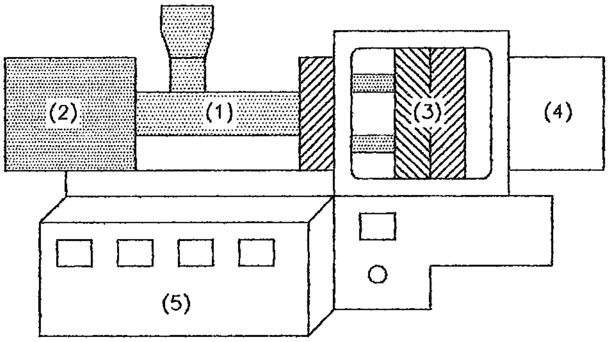

Figure 3.3. Main Sections of an Injection Moulding Machine.

The injection system consists of a hopper, a reciprocating screw and barrel assembly, and an injection nozzle as shown in Figure 3.4. This system confines and transports the plastic as it progresses through the feeding, compressing, degassing, melting, and injection stages.

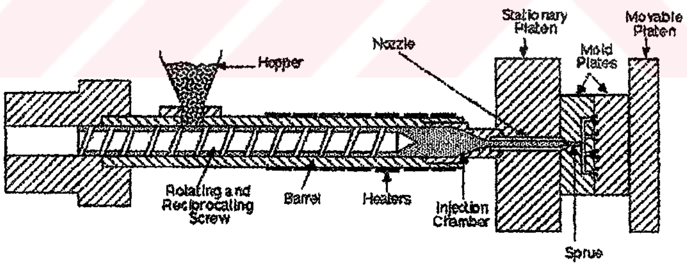

Figure 3.4. Components of a Single Screw Injection Moulding Machine for Thermoplastics.

The hydraulic system on the injection moulding machine provides the power to open and close the mould, build and hold the clamping tonnage, turn the reciprocating screw, drive the reciprocating screw and energize ejector pins and move mould cores. A number of hydraulic components are required to provide this power, which include pumps, valves, hydraulic motors, etc.

The control system provides consistency and repeatability in machine operation. It monitors and controls the processing parameters, including the temperature, pressure, injection speed, screw speed and position, and hydraulic position. The process control has a direct important effect on the final part quality and the economics of the process.

The clamping system opens and closes the mould, supports and carries the relevant parts of the mould, and generates sufficient force to prevent the mould from opening. Clamping force can be generated by a mechanical lock, hydraulic lock, or a combination of the two basic types.

3.4.2. Types of Injection Moulding Machines

There are four basic types of injection moulding machine [20] (Figure 3.5):

1. Conventional injection moulding machine,
2. Piston-type preplastifying machine,
3. Screw-type preplastifying machine,
4. Reciprocating-screw injection machine.

3.4.2.1. Conventional Injection Moulding Machine

In this type of machines, the plastic material is poured into a machine hopper and fed into the chamber of the heating cylinder. A plunger then compresses the material, forcing it through progressively hotter zones of the heating cylinder, where it is spread thin by a torpedo. The torpedo is installed in the center of the cylinder in order to accelerate the heating of the center of the plastic mass. The torpedo may also be heated so that the plastic is heated from the inside as well as from the outside.

The material flows from the heating cylinder through a nozzle into the mould. The nozzle is seal between the cylinder and the mould; it is used to prevent leaking of material caused by the pressure used. The mould is held shut by the clamp end of the machine. The conventional plunger machine is the only type of machine that can produce a mottle-colored moulded part. The other type of injection machines mix the plastic material so throughly that only one color will be produced.

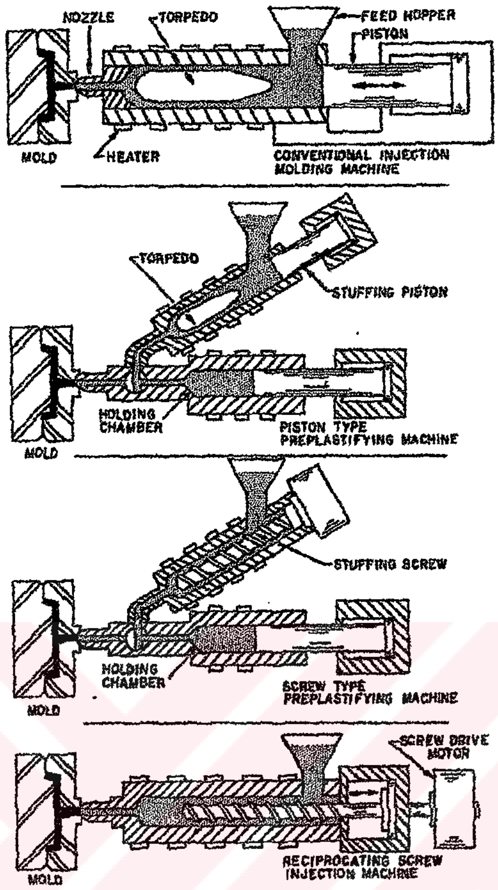

Figure 3.5. Four Basic Types of Injection Moulding Equipment.

3.4.2.2. Piston-Type Preplastifying Machine

This machine employs a torpedo ram heater to preplastify the plastic granules. After the melt stage, the fluid plastic is pushed into a holding chamber until it is ready to be forced into the die. This type of machine produces pieces faster than a conventional machine, because the moulding chamber is filled to shot capacity during the cooling time of the part. Due to the fact that the injection plunger is acting on fluid material, no pressure loss is encountered in compacting the granules. This allows for larger parts with more projected area. The remaining features of a piston-type preplastifying machine are identical to the conventional single-plunger injection machine.

3.4.2.3. Screw-Type Preplastifying Machine

In this injection moulding machine, an extruder is used to plasticize the plastic material. The turning screw feeds the pellets forward to the heated interior surface of the extruder barrel. The molten, plasticized material moves from the extruder into a holding chamber, and from there is forced into the die by the injection plunger. The use of a screw gives the following advantages:

- Better mixing and shear action of the plastic melt,
- A broader range of stiffer flow and heat sensitive materials can be run,
- Color changes can be handled in a shorter time,
- Fewer stresses are obtained in the moulded part.

3.4.2.4. Reciprocating-Screw Injection Machine

This type of injection moulding machine employs a horizontal extruder in place of the heating chamber. The plastic material is moved forward through the extruder barrel by the rotation of a screw. As the material progresses through the heated barrel with the screw, it is changing from the granular condition to the plastic molten state. In the reciprocating screw, the heat delivered to the moulding compound is caused by both friction and conduction between the screw and the walls of the barrel of the extruder. As the material moves forward, the screw backs up to a limit switch that determines the volume of material in front of the extruder barrel. It is at this point that the similarity to a typical extruder ends. On the injection of the material into the die, the screw moves forward to displace the material in the barrel. In this machine, the screw performs as a ram as well as a screw. After the gate sections in the mould have frozen to prevent backflow, the screw begins to rotate and moves backward for the next cycle.

There are several advantages of this method in injection moulding. It more efficiently plasticizes the heat-sensitive materials and blends color more rapidly, due to the mixing action of the screw. The material heat is usually lower and the overall cycle time is shorter.

3.5. TYPES OF MOULDS

An injection mould is usually made in two halves or sections and held together in the closed position by the moulding press. The mould is generally made out of tool steel and is provided with channels for cooling, heating, and venting. Ejector pins and other devices may be incorporated.

There are six basic types of injection moulds in use today [20], as shown in Figures 3.6 and 3.7:

1. Two-plate mould,
2. Three-plate mould,
3. Hot-runner mould,
4. Insulated hot-runner mould,
5. Hot-manifold mould,
6. Stacked mould.

3.5.1. Two-Plate Mould

A two-plate mould consists of two plates with the cavity and cores mounted in either plate. The plates are fastened to the press platens. The moving half of the mould usually contains the ejector mechanism and the runner system. All basic designs for injection moulds have this design concept. A two-plate mould is the most logical type of tool to use parts that require large gates.

3.5.2. Three-Plate Mould

This type of mould is made up of three plates:

- The stationary or runner plate is attached to the stationary platen, and usually contains the sprue and half of the runner.
- The middle plate or cavity plate, which contains half of the runner and the gate, is allowed to float when the mould is open.
- The movable plate or force plate contains the moulded part and the ejector system for the removal of the moulded part.

When the press starts to open, the middle plate and the movable plate move together for releasing the sprue and runner system and degating the moulded part. This type of mould design makes it possible to separate the runner system and the part when the mould opens. The die design makes it possible to use center-pin-point gating.

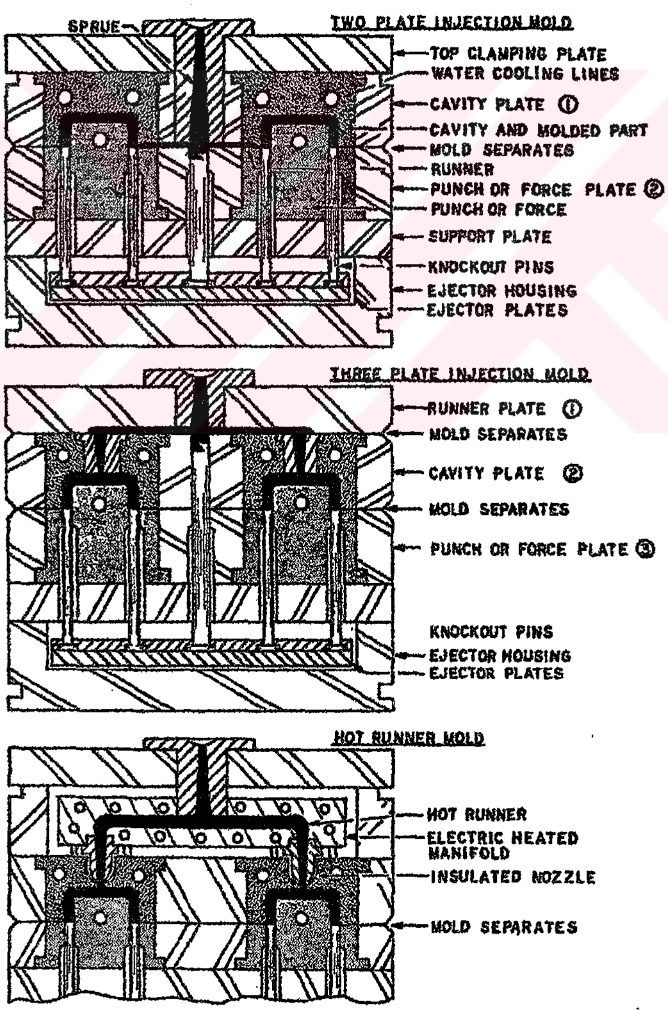

Figure 3.6. Illustration of Three of Six Basic Types of Injection Moulding Dies (See Figure 3.7 for Other Three Types).

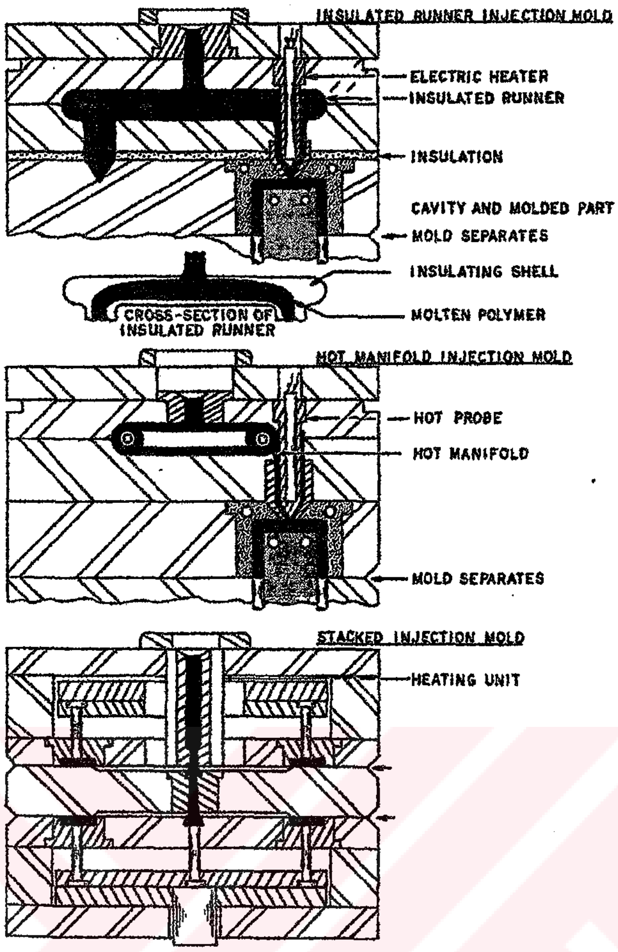

Figure 3.7. Illustration of Three of Six Basic Types of Injection Moulding Dies (See Figure 3.6 for Other Three Types).

3.5.3. Hot-Runner Mould

In this process of injection moulding, the runners are kept hot in order to keep the molten plastic in a fluid state at all times. This is generally known as "runnerless moulding process". In runnerless moulds, the runner is contained in a plate of its own. Hot runner moulds are similar to three-plate injection moulds, except that the runner section of the mould is not opened during the moulding cycle. The heated runner plate is insulated from the rest of the cooled mould. Other than the heated plate for the runner, the remainder of the mould is a standard two-plate die.

Runnerless moulding has several advantages over conventional sprue-runner-type moulding. There are no moulded side products (gates, runners, or sprues) to be disposed of or reused, and there is no separation of the gate from the part. The cycle time is only as long as is required for the moulded part to be cooled and ejected from the mould. In this system, a uniform melt temperature can be supplied from the injection cylinder to the mould cavities.

3.5.4. Insulated Hot-Runner Mould

This is a variation of the hot-runner mould. In this type of moulding, the outer surface of the material in the runner acts like an insulator for the molten material to pass through. In the insulated mould, the moulding material remains molten by retaining its own heat. Sometimes a torpedo and a hot probe are added for more flexibility. This type of mould is ideal for multicavity center-gated parts.

3.4.5. Hot-Manifold Mould

This is another variation of the hot-runner mould. In the hot-manifold die, the runner is heated, however, the runner plate is not. This is done by using an electric-cartridge-insert probe.

3.4.6. Stacked Mould

The stacked injection mould is just what the name implies. A multiple two-plate mould is placed one on top of the other. This construction can also be used with three-plate moulds and hot-runner moulds. A stacked two-mould construction doubles the output from a single press and reduces the clamping pressure required to one half, as compared to a mould of the same number of cavities in a two-plate mould. This method is sometimes called "two-level moulding".

3.6. CLAMPING AND TOGGLE SYSTEMS

Clamping system of injection moulding machines can be classified into three main categories [21]:

- Hydraulic clamping system
- Mechanical clamping system (toggle systems)
- The combination of hydraulic and mechanical systems

3.6.1. Hydraulic Clamping System

Figure 3.8 shows a schematic drawing of an hydraulic clamping system. To the stationary platen (which is attached to the moulding machine) are attached four tie rods which go through and support the moving platen and then through the hydraulic clamping cylinder mounting plate. At each end of the tie rods are tie rod nuts. The hydraulic clamp ram is attached to the moving platen. The stationary side of the mould is attached to the stationary platen. The moving or knockout part of the mould is attached to the moving platen (the knockout or ejection mechanisms of the moulding machine are not shown). The air space in the mould is filled with the molten plastic, and after solidification by cooling it is ejected therefrom.

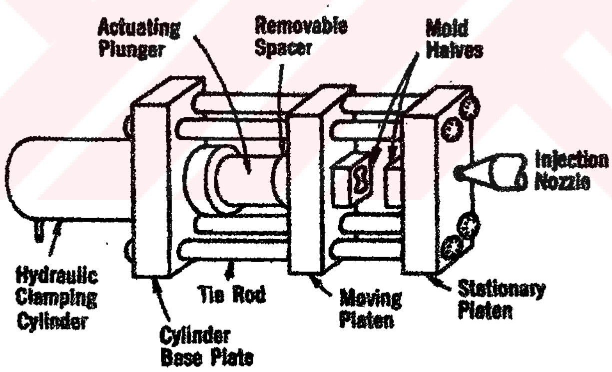

Figure 3.8. Illustration of an Hydraulic Clamp.

It can be seen from Figure 3.8 that when oil is used in the forward port the clamp ram will move the moving until the mould parts make contact. As the prssure builds up, the force behind the clamp ram is transmitted through it, the moving platen, the mould, and the stationary platen to the tie rod nuts. This force stretches the tie bar which provides the clamping action. When the mould is to be opened, oil is sent to the return port and the forward port is vented to a tank. This retracts the clamp ram, moving platen, and moving part of the mould. The plastic part normally remains on the moving part of the mould. The plastic part normally remains on the moving part of the mould and is ejected or knocked out of the mould by the ejection mechanism. The ejecton mechanism can be operated hydraulically, which is preferable because it allows the operator to control the timing, direction, and force of the stroke, or mechanically, wherein the knockout plate is stopped by the knockout bars of the machine.

3.6.2. Toggle Systems

Another type of clamp is the toggle. A "toggle" is a mechanical device to amplify force. In a moulding machine, it consists of two bars joined together end-to-end with a pivot. The end of one bar is attached to a stationary platen and the other end of a second bar is attached to the moveable platen. When the mould is open the toggle is in the shape of a "V". When pressure is applied to the pivot the two bars form a straight line. Mechanical advantage can be as high as 50 : 1. The force straighten the toggle is applied by an hydraulic cylinder.

Figure 3.9 shows a double toggle clamping mechanism. In the mould open position, the hydraulic cylinder has retracted, pulling the crosshead close to the tail stock platen. This pulls the moving platen away from the stationary platen and opens the mould. It is difficult to stop the moving platen before completion of the full stroke. Where this is important to achieve, nylon buffers can be used as a mechanical stop. To close the mould, the hydraulic locking cylinder is extended. The moving plate moves rapidly at first and automatically decelerates as the crosshead extends and straightens out the links. A small motion of the crosshead develops a large mechanical advantage causing the locking.

The two main advantages of a toggle system are the economy of running a much smaller hydraulic cylinder than a comparable fully hydraulic machine and the inherent speed of the design. Fully hydraulic clamps are capable of moving as fast as toggles, but the cost to achieve this is much higher than in an equivalent toggle system. Another advantage of the toggle system is that it is self locking. Once the links have reached their extended position they will remain there until retracted. The hydraulic system requires maintenance of line pressure all the time.

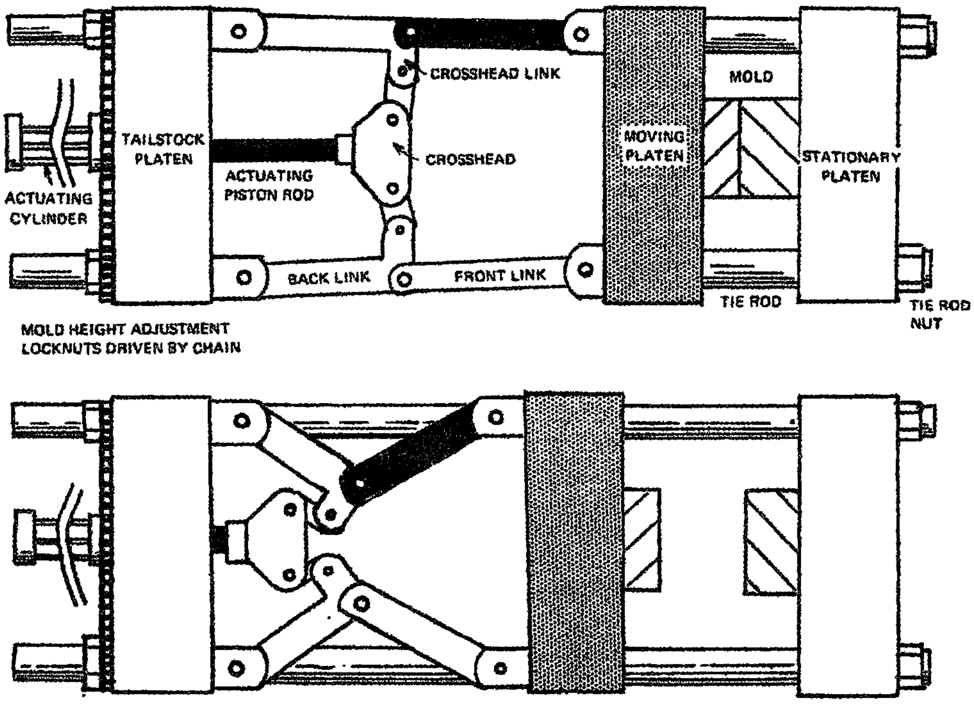

Figure 3.9. Double Toggle Clamping System.

The toggle systems on moulding machines have several disadvantages. The primary one is that there is no indication of the clamping force, and it is therefore difficult to adjust and monitor. The clamping force in an hydraulic system is read immediately by a pressure gauge and can be controlled in stepless increments. It is difficult to control the speed and force of the toggle mechanism, as well as starting and stopping at different points. A major disadvantage of the toggle system is that it requires significantly more maintenance than an hydraulic one. It is susceptible to much more wear.

In order to clamp properly, the toggles must be fully extended. Therefore, the distance of the tail stock platen has to be changed to accommodate different moulds. One way to do this is to have a chain which simultaneously moves the four locking nuts on the tail stock platen. This can be turned mechanically, electrically, or hydraulically.

3.7. RUNNERS, SPRUES AND GATES

3.7.1. Runners

A runner system directs the melt flow from the sprue to the mould cavities. Additional pressure is required to push the melt through the runner system. In addition, shear (frictional) heat generated within the melt while the material is flowing through the runner raises the melt temperature to the proper processing range.

3.7.1.1. Runner Design and Balancing

Although properly sizing a runner to a given part and mould design has a tremendous pay-off, it is often overlooked because the basic principles are not widely understood. While large runners facilitate the flow of material at relatively low pressure requirements, they require a longer cooling time, more material consumption and scrap, and more clamping force. Designing the smallest adequate runner system will maximize efficiency in both raw material use and energy consumption in moulding. At the same time, runner size reduction is constrained by the moulding machine's injection pressure capability. The objectives of runner system design are to determine the number of cavities, deliver melt to the cavities, balance filling of multiple cavities and multi-gate cavities, minimize scrap, eject easily, maximize efficiency in energy consumption, and control the filling/packing/cycle time.

3.7.1.2. Runner Layouts

There are three runner system layouts used for multi-cavity systems [19]:

- The standard (herringbone) runner system
- The "H" bridge (branching) runner system
- The radial (star) runner system

The latter two are considered to be naturally balanced (see Figure 3.10). The naturally balanced runner provides equal distance and runner size from the sprue to all cavities, so that each cavity fills under the same conditions. Although the herringbone is naturally unbalanced, it can accommodate more cavities than its naturally balanced counterparts, with minimum runner volume and less tooling cost. An unbalanced runner system can be artificially balanced by changing the diameter and the length of the runner.

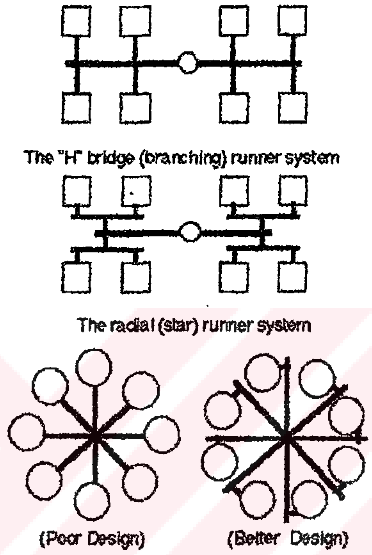

Figure 3.10. Basic Runner System Layouts.

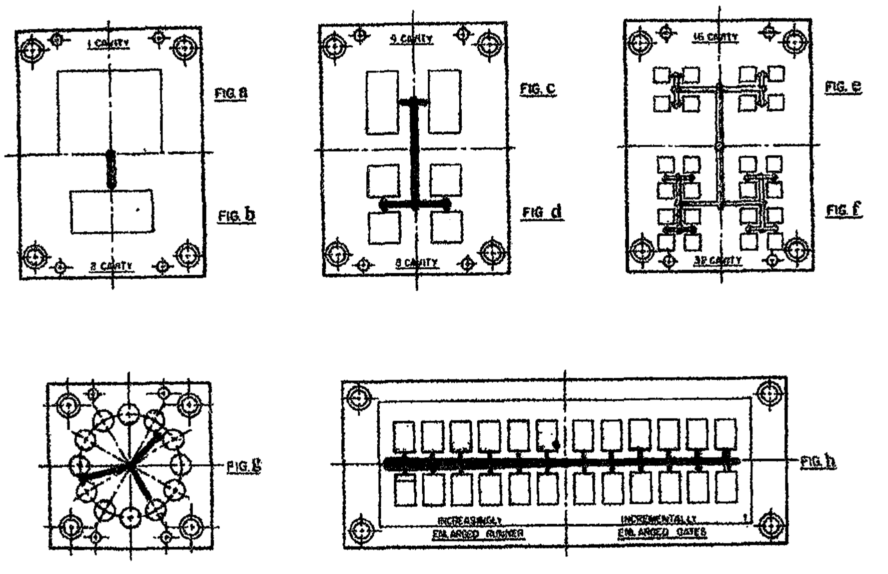

Figure 3.11. Basic Types of Cavity Arrangements.

Figure 3.11 shows how numbers are arranged in the cavity layout. Multiple cavities are arranged so that all are alike and can be manufactured as duplicates. Figures a-f in Figure 3.11 illustrate cavity layouts for single-cavity moulds through thirty-two cavity moulds. Figure g in Figure 3.11 shows circular layout for small parts generally used in very small machines or hot or insulated runner designs. Figure h in Figure 3.11 shows a layout of cavities that causes the runner to get larger as it moves away from the center on the left side or the gates to get larger as shown in on the right side. There are, of course, variation on all of these layouts, but many companies stay with Figures a-f in Figure 3.11 for transportation and construction purposes.

3.7.1.3. Runner Cross Sections

The commonly used runner designs are as follows [19] (see Figure 3.12):

- The full-round runner
- The trapezoidal runner
- The modified trapezoidal runner (a combination of round and trapezoidal runners)
- The half-round runner
- The rectangular runner

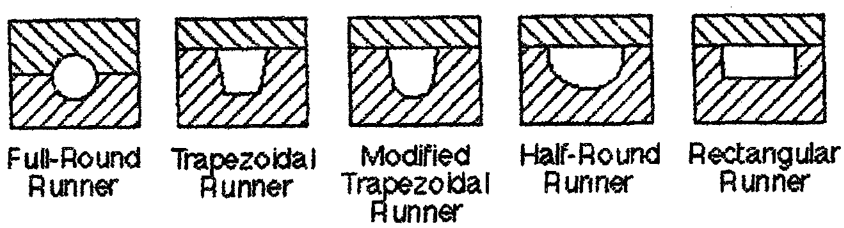

Figure 3.12. Commonly Used Runner Cross Sections.

The first three runner cross-sectional designs are generally recommended. The full-round runner is the best in terms of a maximum volume-to-surface ratio, which minimizes pressure drop and heat loss. However, the tooling cost is generally higher because both halves of the mould must be machined so that the two semi-circular sections are aligned when mould is closed.

The trapezoidal runner also works well and permits the runner to be designed and cut on one side of the mould. It is commonly used in three-plate moulds where the full-round runner may not be released properly, and at the parting line in moulds where the full-round runner interferes with mould sliding action.

3.7.1.4. Runner Balancing

Balanced flow into the cavities is a necessity for a quality part. This can be achieved by changing the runner size and length. Changing the gate dimension may give a seemingly balanced filling. However, it affects the gate freeze-off time greatly, which is destructive to part uniformity. Whenever possible, a naturally balanced runner system should be used to balance the flow of material into the cavities. If a naturally balanced runner is not possible, then the runner system should be artificially balanced.

To balance a runner system, one must encourage flow to the cavities farthest from the sprue by reducing the diameter of runners feeding the other cavities. Note that decreasing runner diameter too much may cause it to freeze earlier time than required, causing a "short-shot". On the other hand, increased frictional shear heating may actually reduce the resin's resistance to flow and fill the cavity even faster. It should be kept in mind that non-standard runner diameters will increase mould manufacturing and maintanence costs.

An artificially balanced runner system designed for one material may not work for others. Further, an artificially balanced runner system requires tighter process controls. A small variation in the process control will alter the filling pattern of the mould, leading to consistently unbalanced filling. Generally speaking, a slow injection rate will first fill parts farther out onto the runner, while a faster injection rate will first fill the parts closest to the sprue. The reason is as follows: at a slower injection rate, the melt tends to hesitate at the restricted gate it first encounters. It moves out to fill the remaining runner system. By the time all the runner branches are filled, the melt at the first, upstream gates may have already become more resistant than the downstream gates, due to solidification. Varied injection speed will result in filling patterns between these two extremes as shown in Figure 3.13.

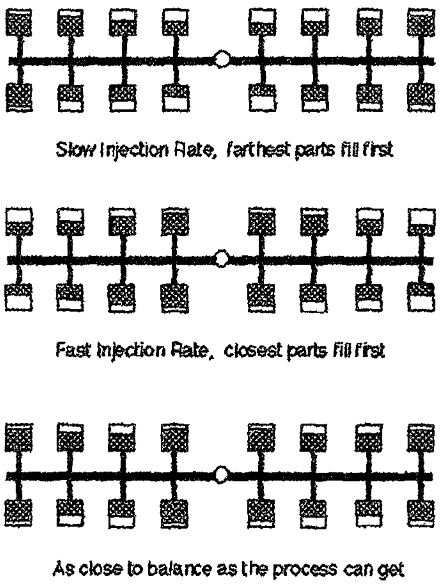

Figure 3.13. Filling Patterns Resulting from Various Injection Rates, in an Unbalanced Runner System.

3.7.2. Sprue

The dimensions of the sprue depend primarily on the dimensions of the moulding and especially its wall thickness. There are some guidelines to be considered:

- The sprue must not freeze before any other cross section in order to permit sufficient transmission of holding pressure.
- The sprue must de-mould easily and reliably.

3.7.3. Gate

A "gate" is a small opening (or orifice) through which the polymer melt enters the cavity. Design of gates is required for reliable injection moulding process. In addition, selection of the appropriate gate is another problem which can be encountered.

3.7.3.1. Gate Design

Gate design for a particular application includes selection of the gate type, dimensions, and location. It is dictated by; the part and mould design, the part specifications (appearance, tolerance, concentricity, etc.), the type of material being moulded, the fillers, the type of mould plates, and economic factors (tooling cost, cycle time, allowable scrap volume, etc.). Gate design is of great importance to part quality and productivity. Unless it is necessary to use multiple gates (e.g., the length of melt flow exceeds practical limits), a single gate is generally preferred. Multiple gates always create problems of weld and meld lines.

The cross section of the gate is typically smaller than that of the runner and the part so that the part can be easily "de-gated" (separated from the runner). Technically speaking, the material's freeze-off at the gate marks the end of packing the cavity. A larger gate dimension will reduce viscous (frictional) heating, permit lower velocities, and allow the application of high packing pressure to increase the density of the material in the cavity. If low stress is a requirement, due to concerns of aesthetic appearance or dimensional stability, a larger gate may be necessary.

The gate location should be selected in such a way that rapid and uniform mould filling is ensured and the weld/meld lines (if any) and air vents are positioned properly. The gate should be positioned away from load-bearing areas. This is because the high melt pressure and high velocity of flowing material at a gate cause the area near a gate to be highly stressed.

3.7.3.2. Gate Types

Gates can be classified into two main categories, based on the method of de-gating [19]:

- Manually trimmed gates
- Automatically trimmed gates

3.7.3.2.1. Manually trimmed gates

Following are the gate types that are trimmed from the cavity manually (see also Figures 3.14-16):

- Direct (or sprue) gate: A direct (or sprue) gate is commonly used for single-cavity moulds where the sprue feeds material directly into the cavity rapidly with minimum pressure drop. The disadvantage of using this type of gate is the gate mark left on the part surface after the runner (or sprue) is trimmed off.

- Tab gate: A tab gate is typically employed for flat and thin parts, to reduce the shear stress in the cavity. The high shear stress generated around the gate is confined to the auxiliary tab, which is trimmed off after moulding. A tab gate is used extensively for moulding PC, acrylic, SAN, and ABS types of materials.

- Edge (or standard) gate: An edge gate is located on the parting line of the mould and typically fills the part from the side, top, or bottom of a part.

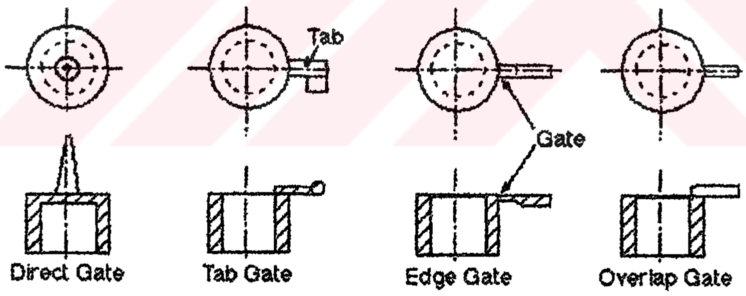

Figure 3.14. Direct, Tab, Edge and Overlap Gates.

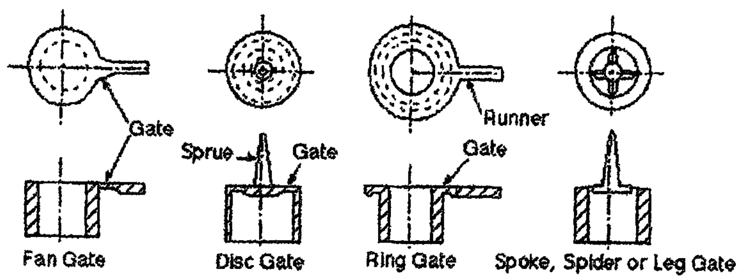

Figure 3.15. Fan, Disk, Ring and Spoke Gates.

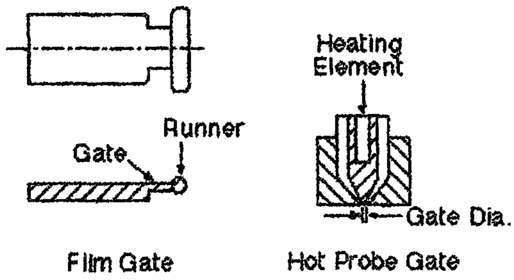

Figure 3.16. Film and Hot Probe Gates.

- <u>Overlap gate:</u> An overlap gate is similar to an edge gate except the gate overlaps the wall or surfaces.

- <u>Fan gate:</u> A fan gate is a wide edge gate with variable thickness. It permits rapid filling of large parts of fragile mould sections through a large entry area. It is used to create a uniform flow front into wide parts where warpage and dimensional stability are main concerns.

- <u>Disc (or diaphragm) gate:</u> A diaphragm gate is often used for gating cylindrical or round parts that have an open inside diameter. It is used when concentricity is an important dimensional requirement and the presence of a weld line is objectionable.

- <u>Ring gate:</u> A ring gate is also used, but not always recommended, for cylindrical or round parts. With a ring gate, the material flows freely around the core before it moves down as a uniform tube-like extrusion to fill the mould.

- <u>Spoke (or spider) gate:</u> This kind of gate is also called a four-point gate or cross gate. It is used for tube-shaped parts and offers easy de-gating and material saving. Disadvantages are the possibility of weld lines and the fact that perfect roundness is unlikely.

- <u>Film (or flash) gate:</u> A film gate is similar to a ring gate, but it is used for straight edges. It consists of a straight runner and a gate land across either the entire length or width of the cavity or a portion of the cavity. It is used for acrylic parts, and generally for flat designs of large areas where warpage must be kept minimum.

- Hot-probe gate: A hot-probe gate or hot runner gate is generally used to deliver material through heated runners directly into the cavity, producing runnerless mouldings.

3.7.3.2.2. Automatically trimmed gates

Following are the gate types that are trimmed from the cavity automatically (see also Figure 3.17):

- Pin gate: A pin (or pinpoint) gate is generally used in either three-plate moulds or hot runner moulds for rapid gate freeze-off and easy de-gating. The runner is automatically trimmed from the part with a stripper plate as the mould opens.

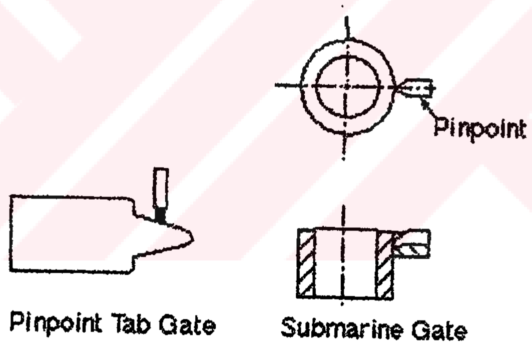

Figure 3.17. Pin and Submarine Gates.

- Submarine (or tunnel, chisel) gate: A submarine gate is used in two-plate moulds or in multi-cavity moulds. It is made by machining a tapered (angled) tunnel from the edge of the gate runner to the cavity just below the parting line. It permits automatic de-gating of the part from the runner system during the ejection stage. It is tapered to the spherical side of the runner.

3.8. ADVANTAGES AND DISADVANTAGES OF THE INJECTION MOULDING PROCESS

3.8.1. Advantages of Injection Moulding

There are several advantages of the injection moulding process compared to other plastic forming methods [22]:

1. Parts can be produced at high production rates.
2. Large volume production is possible.
3. Relatively low labour cost per unit is obtainable.
4. Process is higly susceptible to automation.
5. Parts require little or no finishing.
6. Many different surfaces, colors, and finishes are available.
7. Good decoration is possible.
8. For many shapes, this process is the most economical way to fabricate.
9. Process permits the manufacture of very small parts which are almost impossible to fabricate in quantities by other methods.
10. Minimal scrap loss result as runners, gates, and rejects can be reground and reused.
11. Same item can be moulded in different materials, without changing the machine or mould in some cases.
12. Close dimensional tolerances can be maintained.
13. Parts can be moulded with metallic and nonmetallic inserts.
14. Parts can be moulded in a combination of plastic and such filters as glass, asbestos, talc, and carbon.
15. The inherent properties of the material give many advantages such as high strength-weight rates, corrosion resistance, strength, and clarity.

3.8.2. Disadvantages and Problems of Injection Moulding

The injection moulding process has some disadvantages and bottlenecks compared to other plastic forming methods [22]:

1. Intense industry competition often results in low profit margins.
2. Three shift operations are necessary to compete.
3. Mould costs are high.
4. Moulding machinery and auxiliary equipment costs are high.
5. Process control may be poor.
6. Susceptibility to poor workmanship.
7. Quality is often difficult to determine immediately.
8. Lack of knowledge about the fundamentals of the process causes problems.
9. Lack of knowledge about the long term properties of the materials may result in long-term failures.

Many of the above problems can be eliminated if the processor understands the operation of the machines and the plastics processing principles.

CHAPTER IV

ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS

4.1. INTRODUCTION

This chapter is devoted to the detailed information about Artificial Intelligence (AI) and Expert Systems (ESs). Section 4.2 gives a brief description of Artificial Intelligence (AI). Sections 4.3.1-3 provide brief information about artificial intelligence techniques such as Genetic Algorithms (GAs), Artificial Neural Networks (ANNs), and Fuzzy Logic (FL). The history and definition of expert systems are given in Sections 4.4 and 4.5. Section 4.6 and 4.7 include the participants and components of an expert expert system. Section 4.8 discusses the major differences between database file and a Knowledge Base (KB). The comparison of expert systems and conventional computer programming is done in Section 4.9. Section 4.10 explains the programming techniques to develop an expert system. The reasons to use an expert system are given in Section 4.11. Section 4.12 shows the application areas of expert systems. Finally, some of the advantages and disadvantages of expert systems are listed in Sections 4.13 and 4.14.

4.2. DEFINITION OF ARTIFICIAL INTELLIGENCE (AI)

Some definitions of "Artificial Intelligence" are [23]:

- The power of meeting any situation succesfully by proper behaviour adjustments.
- The ability to understand interrelationships of presented facts in a such way as to guide action toward a desired goal.

These definitions can just as well be applied to the behaviour of a machine as to that of a human. Intelligence is multipurpose and involves the ability to learn, and we shall have much to say about the desirability of incorporating these aspects of intelligence into heuristic programs. The goal of work in artificial intelligence is to build machines that perform tasks normally requiring human intelligence.

4.3. ARTIFICIAL INTELLIGENCE TECHNIQUES

AI based techniques are designed for capturing, representing, organizing, and utilizing knowledge by computers, and hence play an important role in the intelligent manufacturing. AI has provided several techniques with applications in manufacturing like; Fuzzy Logic (FL), Expert Systems (ESs), Artificial Neural Networks (ANNs), Genetic Algorithms (GAs), etc.

4.3.1 Genetic Algorithms (GAs)

Genetic algorithms are search algorithms based on the mechanics of neural selection and neural genetics. They combine survival of the fittest among string structures with a structured yet optimized information exchange to form a search algorithm.

In every generation, a new set of artificial creatures (strings) is created using bits and pieces of the fittest of the old; an occasional new part is tried for good measure. While randomized, genetic algorithms are no simple random walk. They efficiently benefit from historical information to estimate new search points with expected improved performance [24].

Genetic algorithms are different from more normal optimization and search procedures in four ways [24]:

1. GAs work with a coding of the parameter set, not the parameters themselves.
2. GAs search from a population of points, not a single point.
3. GAs use payoff (objective function) information, not derivatives or other auxiliary knowledge.
4. GAs use probabilistic transition rules, not deterministic rules.

4.3.2. Artificial Neural Networks (ANNs)

An Artificial Neural Network (ANN) System is a hardware or software that attempts to emulate the processing patterns of the biological brain [25]. Neural networks are systems composed of many simple processing elements (i.e., neurons) operating in parallel and whose functions are determined primarily by the pattern of connectivity. These systems are capable of high-level functions, such as adaptation or learning, and lower level functions such as data pre-processing for different kinds of inputs. Neural networks have been inspired both by biological nervous systems and mathematical theories of learning, information processing and control [26].

There are some differences between Expert Systems (ESs) and Artificial Neural Networks (ANNs). Expert Systems (ESs), like most traditional systems, seek [illegible] of problems. The resulting

classes of problems.

On the other hand, unlike Expert Systems (ESs) which typically can provide explanations for their solutions, Neural Networks (ANNs) cannot always explain why they arrived at a particular solution. Moreover, neural nets cannot always guarantee a completely certain solution, cannot always arrive at the same solution again with the same input data, or cannot always guarantee the "best" solution. However, these examples suggest that in most current applications, neural networks are best used as aids to human decision makers instead of substitutes for them [25].

4.3.3. Fuzzy Logic (FL)

Fuzzy Logic (FL) is another tool of AI that is gaining popularity in recent times. It is based on the observation that people make decisions based on uncertain and non-numerical information, fuzzy models or sets are mathematical means of representing vagueness and imprecise information, hence the term "fuzzy". These models have the capability of recognizing, representing, manipulating, interpreting, and utilizing data and information that are vague and lack certainity [26]. Linguistic examples are: *a few, almost all, more or less, very important, good, poor, appropriate, acceptable*, etc.

The basic idea behind the FL is quite simple. An exact rule or law cannot be defined for each possible problem. For these cases, humans approximate well solutions to the problems. This approximation is possibly due to the flexibility in the definition of the *words* that constitute the rules. Hence, human logic is very flexible. FL simulates this human logic using a mathematical model [26]. However, the nature of this simulation is different from that of ANNs. ANNs simulate the humans' nervous system and deals with the learning ability, whereas FL mainly deals with the decision making processes performed by humans based on linguistic terms.

Fuzzy logic has been mainly suggested to handle fuzzy concepts, inexact information, and approximate reasoning in expert systems. In fuzzy logic, system behaviour can simply be described with a simple rule base containing many "if-then" rules. Therefore in FL, the knowledge representation is explicit, the verification is easy and optimization of the system performance is possible. On the other hand, FL has no training ability. Trainability is the most important function of ANNs. Therefore, if the explicit knowledge representation capability of fuzzy logic is combined with the learning power of ANNs, a more powerful technology can be obtained. Such systems are called **"Neuro-Fuzzy Systems"**.

4.4. EXPERT SYSTEMS (ESs)

Expert Systems (ESs) grew out of the computer science field of artificial intelligence, but today they are not prized for their ability to imitate humans as much as they are for their ability to solve difficult problems. Expert systems have suffered from unrealistic expectations that arose from their association with the field of artificial intelligence.

In the early 1980s, people expected that expert systems would revolutionize computing and displace conventional computer systems. When this did not happen, the general comment was that expert systems had failed [27].

In fact, exactly the opposite had happened: expert systems had become another tool that software engineers could use to solve problems. Instead of revolutionizing computing, expert systems had become a step in the development of computing in general. As computer science has developed, so have the tools in the software engineer's toolbox: conventional languages, fourth-generation languages (high-level languages that generate blocks of code), and expert system development tools.

4.5. DEFINITION OF AN EXPERT SYSTEM

An Expert System (ES) is a computer program that uses knowledge and reasoning techniques to solve problems that are difficult enough requiring significant human expertise for their solution [28]. An expert system may emulate the external behaviour of an expert (i.e., gathering information and producing solutions to problems), or it may attempt to closely model the internal mental processes of the expert as well. In any event, most expert systems have the ability to justify or explain the reasons behind a specific problem solution.

An important subset of the general area of expert systems concentrates on explicitly representing an expert's knowledge about a class of problems and providing a separate reasoning mechanism (usually called an "inference engine") that operates on this knowledge to produce a solution. These kind of systems are called "Knowledge-Based Expert Systems (KB-ESs)" which are the subclasses of ESs as shown in Figure 4.1.

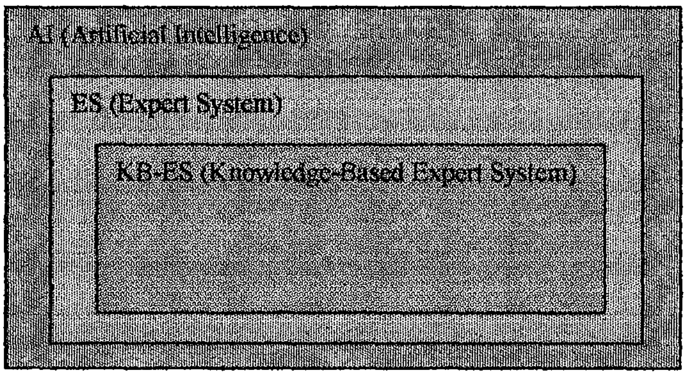

Figure 4.1. [illegible] of ESs and KB-ESs.

4.6. PARTICIPANTS OF AN EXPERT SYSTEM

To develop an expert system, contribution of different disciplines may be required [28].

4.6.1. Domain Expert

A domain expert is a specialist in a particular field with the ability to apply that knowledge to solve problems and make decisions.

4.6.2. Knowledge Engineer

Knowledge engineers are concerned with identifying the specific knowledge that an expert uses in solving a problem. Initially, the knowledge engineer studies a human expert and determines what facts and rules of thumb the expert employs. Then, the knowledge engineer determines the inference strategy that the expert uses in an actual problem-solving situation. Finally, the knowledge engineer develops a system that uses similar knowledge and inference strategies to simulate the expert's behaviour.

4.6.3. Knowledge Base Author

A knowledge base author translates the information obtained from domain experts into a knowledge base using an expert system language. The knowledge base author can be a domain expert, a knowledge engineer, or both.

4.6.4. End User

The end user uses the expert system to solve a problem.

4.7. COMPONENTS OF AN EXPERT SYSTEM

An expert system consists of four major components (see Figure 4.2) [28].

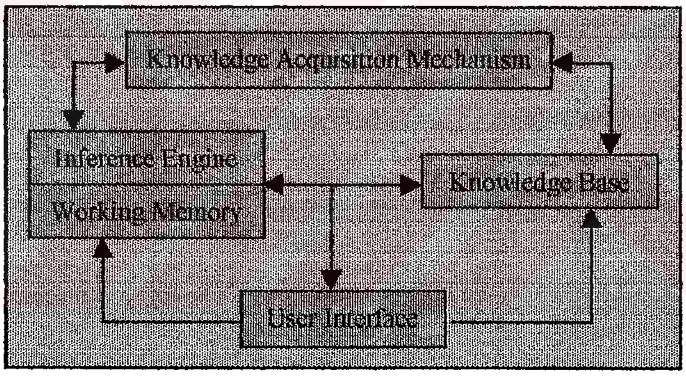

Figure 4.2. Components of an Expert System.

4.7.1. User Interface

User interface enables a tutor to set up and maintain the expert system, and prepare the knowledge to be entered into the knowledge database.

4.7.2. Knowledge Base

The Knowledge Base (KB) is a file containing the facts and heuristics that make up an expert's knowledge. The knowledge base is structured by IF-THEN rules or frames, with series of questions. When an expert system is run, the inference engine uses the knowledge provided in the knowledge base and information obtained from the end user to solve problems.

4.7.3. Knowledge Acquisition Mechanism

Knowledge acquisition mechanism is used to acquire human expertise and transform into the knowledge base. This module processes the data entered by the expert and transforms it into a data presentation understood by the system.

4.7.4. Inference Engine

Inference engine is the knowledge processor which looks at the problem description and tries to find a solution. It can be considered as a program that applies domain knowledge to known facts to draw conclusions. Inference engines are "domain independent", that is, they apply domain knowledge to case-specific information. Inference engines vary according to:

- Required representation of knowledge
- Strategy for applying the knowledge
- How uncertainity is handled

4.8. DIFFERENCE BETWEEN A DATABASE FILE AND A KNOWLEDGE BASE (KB) FILE

Databases (and data base management systems) were originally developed to maintain records involving large volumes of data. Sophisticated data base methods allow entities and their relationships to be represented, so data base may also be viewed as a model of its domain. Thus, in a data base, knowledge about the domain may be implicitly represented by the structure of the database. The actual contents of a data base are the facts, data, or information, rather than knowledge.

Expert Systems (ESs), on the other hand, are more directly related to solving problems (not restricted to maintaining records), based on how a human expert approaches a task. Knowledge about the problem is explicitly represented in the knowledge base; thus, a knowledge base consists of all of the methods the expert uses to perform a task. These methods may include computer programs, rules of thumb, theories, logic, or any number of other approaches. In contrast to most data bases, when this explicitly represented knowledge is combined with facts about a specific problem situation, the expert system is able to produce a solution to the problem.

4.9. HOW DO EXPERT SYSTEMS DIFFER FROM CONVENTIONAL COMPUTER PROGRAMMING

Expert systems differ from conventional programs in several ways [27]:

- The type of information encoded in them.
- The techniques used for encoding information.
- The methodology used to build them.

4.9.1. Type of Information

Conventional programs contain algorithmic data, i.e., specific, sequential instructions that tell the computer how to solve problems. Expert systems, on the other hand, contain declarative data which have statements of "what" instead of "how". Often the very reason an expert system is used is that there is no known algorithm for solving a problem, or there may be more than one acceptable solution.

An example of an algorithmic solution would be that of a payroll system, in which all the exact instructions to solve the problem are known in advance and can be encoded in a conventional language, and for which there is only one correct answer. An example of an expert system solution would be an airline gate scheduling system, where the solution varies so much with context that sequential instructions would not reasonably handle all of the possible situations. An expert system would be most appropriate for solving this problem, and could consist of rules that state what action should be taken if certain conditions exist, for example:

If

a gate is required for arriving Plane A of a certain size

and there are no gates available for this plane at arrival time

and another Plane B is scheduled to a gate which could take Plane A

and there is another gate free which could take Plane B

then

reschedule Plane B to the available gate, freeing up the gate for Plane A.

4.9.2. Techniques Used

While conventional systems are developed using sequential computer languages such as C, Pascal, FORTRAN, Ada, COBOL, and BASIC; expert systems are often built using higher-level languages and tools such as LISP, Prolog, KES, and VP-Expert. Often, these languages and tools have a built-in reasoning capability that allows the knowledge engineer or software engineer to write expert systems without having to implement the reasoning (or inferencing) mechanism. These tools usually focus on symbolic processing, rather than on numeric computation. Another useful set of expert system development tools is the growing set of object-oriented tools available. As their name indicates, these tools treat the subjects of a problem as objects.

In the previous example, if this type of tool were used in an airline gate scheduling system, each gate would be an object, and its features would be associated with it as attributes in a completely symbolic representation. The object of gate, for instance, would have a set of attributes, including its location and the type of aircraft it can accommodate.

4.9.3. Methodology

Although many characteristics of the conventional software development cycle apply to expert systems, the nature of expert systems causes them to require additional techniques. In conventional software projects, it is usually possible to obtain user requirements, design software to meet those needs, develop and deliver the completed application to the users. Expert system projects, however, require an iterative approach, in which successive prototypes of the system are developed and brought back to users and experts for comment.

4.10. REASONING METHODOLOGIES IN EXPERT SYSTEMS

There are three types of techniques (approaches) in LISP programming language in order to find a solution to a problem [29,30]:

4.10.1. Forward Chaining (FC)

"Forward Chaining (FC)" method is used to infer all possible solutions from given information. In forward chaining, when one rule fires and asserts values and assertions that match the antecedents ("IF" part of a rule) of other forward or bidirectional (i.e., rules that can fire both in forward and backward directions) rules, the system can then fire these rules, asserting more values and creating more assertions, initiating further forward chaining. The system forward chains until there are no more forward or bidirectional rules whose antecedents match objects in the knowledge base.

4.10.2. Backward Chaining (BC)

"Backward Chaining (BC)" method enables you to direct your search toward a particular goal by using the reverse of the algorithm used in forward chaining. It is supposed that the application is large, and only particular or partial amount of the problem will be considered. If forward chaining is used for the solution, resources will be used searching for solutions which might not be needed. Instead, it is more efficient to consider only that particular amount of the problem as a goal, and using backward chaining to solve for that one goal. In other words, "backwards" for a sequence of rules, which can be asserted the goal into the system, will be searched.

Therefore, backward chaining prevents the system to use resources more than necessary.

4.10.3. Goal-Directed Forward Chaining (GD-FC)

There is a different method in LISP programming language called "Goal-Directed Forward Chaining (GD-FC)". This method enables you to fire forward rules during backward chaining. For this purpose, an *enabling pattern* is associated with a collection of forward rules in a rule set (a rule package consisting of particular forward rules for a particular goal). Enabling pattern includes the information about a particular case of problem. During the query or searching phase of program, enabling pattern matches an attempt, which contains the information of query, or subattempt pattern that has been queried. Then, the system activates the rule set, so that the rules in the rules set are added to the list of active rules. Backward chaining is then suspended while the system performs all forward chaining possible with those rules. These forward rules can possibly assert the goal pattern which is searched for, thus minimizing the need to continue the backward chain. This can save time and resources when the application is running.

4.11. WHY USE AN EXPERT SYSTEM

As a summary, Expert Systems (ESs) can help solve problems that cannot be handled effectively by conventional systems. The types of problems that normally lend themselves to successful expert system solutions include diagnosis, configuration, planning, scheduling, selection, matching, and routing. Many of these tasks have the characteristics listed below [27]:

- The problem cannot be solved easily using a conventional solution because:
  - no algorithm is known for solving it completely,
  - the problem is too complex to be represented in conventional programming languages.

- The problem requires primarily symbolic, not numeric, reasoning.
- A tool is needed to facilitate rapid prototyping (building an early version of the application), for recoding later in a conventional language.

In general, if the problem can be solved without expert systems technology, a conventional solution should be used. Good software engineering practices dictate using the most appropriate tool for the task. Additionally, special skills need not be developed and used unless they are necessary. Some expert system-building tools are also more resource-intensive than conventional tools and need either more computer power or more time to execute. There is no reason to use a specialized tool unless the problem requires it.

4.12. WHAT CAN BE DONE WITH AN EXPERT SYSTEM

An expert system can be used to perform a variety of tasks. An expert system can be created to:

- Diagnose medical problems (e.g., determination of disease of a human, or a fish)
- Diagnose equipment failure (e.g., finding what is wrong with your car, or machine)
- Interpret chemical data
- Make financial decisions
- Interpret signals
- Predict locations of mineral deposits
- Give advice about computer system use (e.g., on using how operating system works)

4.13. ADVANTAGES OF EXPERT SYSTEMS

Some advantages of expert systems can be summarized as follows:

- Expert systems can accommodate new expertise whenever new knowledge is identified.
- Expert systems are able to explain their recommendations.
- Expert systems can apply heuristics to reduce the complexity of search.
- Expert systems reduce the company's reliance on human experts by capturing expert knowledge and store the knowledge in computers.

4.14. DISADVANTAGES OF EXPERT SYSTEMS

Although expert systems is a powerful AI tool, there are some disadvantages of them:

- Expert systems can not perform "creative" intellectual processes such as inventing a product name or resolving personal disputes.
- They have only a narrow range of knowledge, and lack human "common sense". They're best for "dumb complexity", such as deciding whether you qualify for a tax exemption or finding what's wrong with your car.
- Many expert systems refer about "20%" of cases to a human specialist.
- Humans are also needed if you want to make changes to the system.

CHAPTER V

INJECTION MOULDING PARAMETERS

5.1. INTRODUCTION

There are several parameters of a Plastic Injection Moulding Machine (PIMM). Some of them are directly affecting the process, therefore, they are called "quantifiable attributes". On the other hand, some of them are used only as a switched parameter, therefore, they are known as "on-off attributes". These parameters can be grouped into three main category [31]:

1. Parameters related to the injection unit of the PIMM
2. Parameters related to the clamping unit of the PIMM
3. Parameters related to the other units of the PIMM (general parameters)

This chapter gives detailed information about these parameters. Section 5.2 consists of parameters related to the injection unit of a PIMM. Section 5.3 includes parameters related to the clamping unit of a PIMM. Parameters related to other units of a PIMM are discussed in Section 5.4. Finally, Section 5.5 contains a brief conclusion.

5.2. INJECTION UNIT ATTRIBUTES

5.2.1. Screw Diameter

For a given injection unit, most manufacturers offer a choice of screw diameters. The screw diameter directly affects the L/D ratio (see also Section 5.2.4) and the injection volume (and hence, the shot weight).

5.2.2. Shot Weight

Shot weight is an important attribute of the injection unit of a PIMM expressed in ounces or grams. This parameter is the most commonly used single attribute to select a plastic injection moulding machine. A moulder has an article at hand to be moulded. Once the plastic material is selected, it has a weight. A PIMM with sufficient shot weight is then selected.

Table 5.1. Specific Gravity of Resins at Room Temperature [31].

Resin	Abbreviation	S.G. at room temperature
General Purpose Polystyrene	GPPS (PS)	1.04 - 1.09
High Impact Polystyrene	HIPS	1.14 - 1.20
Acrylonitrile Butadiene Styrene	ABS	1.01 - 1.08
Acrylonitrile Styrene	AS (SAN)	1.06 - 1.10
Low Density Polyethylene	LDPE	0.89 - 0.93
High Density Polyethylene	HDPE	0.94 - 0.98
Polypropylene	PP	0.85 - 0.92
Plasticized Polyvinyl Chloride (soft)	PPVC	1.19 - 1.35
Unplasticized Polyvinyl Chloride (rigid)	UPVC	1.38 - 1.41
Polyamide-6	PA-6	1.12 - 1.15
Polyamide-66	PA-66	1.13 - 1.16
Polymethyl Methacrylate	PMMA	1.16 - 1.20
Polycarbonate	PC	1.20 - 1.22
Polyoxymethylene (Polyacetal)	POM	1.41 - 1.43
Polyethylene Terephthalate	PET	1.29 - 1.41
Polybutylene Terephthalate	PBT	1.30 - 1.38
Cellulose Acetate	CA	1.25 - 1.35
Polyphenylene Oxide, modified	PPO-M	1.04 - 1.10
Polyphenylene Sulfide	PPS	1.28 - 1.32

The shot weight is the measured (actual) weight of the injected plastic when the nozzle is free-standing (i.e., not held against the mould). Table 5.1 lists the

Specific Gravity (SG) of some common resins at room temperature. The plastic used is usually Polystyrene (PS) with a SG of 1.05.

If the article to be moulded is made of a resin different than PS, then the shot weight in the specification could not be used immediately, but must be calculated as follows [31]:

$$S_{resin} = \frac{S_{PS} * SG_{resin}}{SG_{PS}} \tag{5.1}$$

where S_{resin} is the shot weight in terms of resin (g), S_{PS} is the shot weight in terms of PS (g), SG_{resin} is the Specific Gravity (S.G.) of resin at room temperature, and SG_{PS} is the SG of PS at room temperature.

On the other hand, actual shot weight of a machine is not the same with the shot weight of a resin. There is a gain of 80% of the theoretical shot weight value, and this is known as "80% rule" [31]. Thus, the actual shot weight can be found as:

$$S_{machine} = \frac{S_{resin}}{0.8} \tag{5.2}$$

where $S_{machine}$ is the shot capacity of machine (g).

5.2.3. Relation of Shot Weight to Injection Volume

Shot weight is not equal to injection volume times the S.G. of PS. Shot weight is a measurable quantity. Injection volume is, however, theoretical (see also Section 5.2.7). Injection volume times the S.G. of PS provides a higher value than shot weight due to leakage pass in the screw during injection.

Shot weight of a resin in terms of PS could be found as [31]:

$$S_{resin} = SG_{PS} * IV_{act} \tag{5.3}$$

where IV_{act} is actual or calculated injection volume (cm^3). Actual injection volume can be found by means of "90% rule" [31] as follows:

$$IV_{act} = 0.9 * IV_{theo} \tag{5.4}$$

where IV_{theo} is the theoretical injection volume (cm^3).

Some manufacturers prefer to use injection volume as the starting point to state the shot weight of their machines, instead of using measured shot weight. There is a bottleneck in calculating actual shot capacity of machine. Shot weight should not be equal to the combined weight of the article (or articles for a multi-cavity mould). Weight of the runners must be taken into consideration. Generally, weight of the runners can be about 10% of the total weight of cavities. The length and type of arrangement of a runner must also be known when runners are decided to be used in calculations. However, there is insufficient knowledge about the length of the runners. Therefore, the runners are not taken into consideration in this study.

5.2.4. Screw L/D Ratio

For machines that provide a choice of screws, the screw diameter and hence the L/D ratio is an important attribute in the selection process.

The L/D ratio of 22:1 or above provides better mixing and more uniform heating due to compression in the transition section of the screw [31]. It is selected for moulding parts with high requirement such as moulding of engineering thermoplastics or high precision parts. For a given L, a higher L/D ratio translates to a smaller screw diameter. The injection pressure is increased, thus the injection volume and the shot weight are reduced.

A medium L/D ratio of 20:1 is used for general applications with medium requirement [31]. A lower L/D ratio of 18:1 or lower is used for low requirement where shot weight is the more dominant selection criterion [31]. The injection pressure is low.

5.2.5. Injection Pressure

Injection pressure means the maximum pressure in the barrel during injection, not the maximum hydraulic pressure. Usually, injection pressure is higher than the maximum hydraulic pressure by about 10 times [31]. The smaller diameter screw produces the higher injection pressure, thus this helps in moulding of engineering thermoplastics. Material manufacturers publish minimum and maximum injection pressures in the specification of the materials.

5.2.6. Injection Stroke

For a given screw diameter, injection volume could be increased by injection stroke (see also Section 5.2.7). Increasing injection stroke, however, increases the injection time and hence, the cycle time. It also reduces the effective screw length and the effective L/D ratio. Therefore, the advantages of a high L/D ratio is lost.

5.2.7. Injection Volume

Injection volume is a theoretical attribute. It could be obtained by [31]:

$$IV_{theo} = \frac{\pi * d_{screw}^2 * SS}{4} \tag{5.5}$$

where d_{screw} is screw diameter (cm) and SS is screw or injection stroke (cm).

Due to leakage pass in the screw tip and the backward movement of the non-return valve, the actual injection volume is about 90% of the theoretical injection volume. This is known as "90% rule" [31]. To convert the actual injection volume to shot weight, S.G. of the resin at plasticizing temperature is used:

$$IV_{act} = 0.9 * SG_{plast} * IV_{theo} \tag{5.6}$$

where SG_{plast} is the SG of the resin at plasticizing temperature. Specific gravity of resins at plasticizing temperature is shown in Table 5.2. Instead of using shot weight and the "80% rule" in selecting a PIMM, some manufacturers recommend using injection volume as the selection parameter.

Table 5.2. Specific Gravity of Resins at Plasticizing Temperature [31].

Resin	Abbreviation	S.G. at plasticizing temperature
General Purpose Polystyrene	GPPS (PS)	0.886 - 0.901
High Impact Polystyrene	HIPS	0.895 - 0.917
Acrylonitrile Butadiene Styrene	ABS	0.895 - 0.908
Acrylonitrile Styrene	AS (SAN)	0.907 - 0.917
Low Density Polyethylene	LDPE	0.730 - 0.740
High Density Polyethylene	HDPE	0.752 - 0.772
Polypropylene	PP	0.712 - 0.737
Plasticized Polyvinyl Chloride (soft)	PPVC	1.050 - 1.389
Unplasticized Polyvinyl Chloride (rigid)	UPVC	1.134 - 1.219
Polyamide-6	PA-6	0.958 - 0.995
Polyamide-66	PA-66	0.958 - 0.995
Polymethyl Methacrylate	PMMA	0.996 - 1.012
Polycarbonate	PC	1.018 - 1.037
Polyoxymethylene (Polyacetal)	POM	1.187 - 1.214
Polyethylene Terephthalate	PET	1.129 - 1.172
Polybutylene Terephthalate	PBT	1.102 - 1.113
Cellulose Acetate	CA	1.074 - 1.104
Polyphenylene Oxide, modified	PPO-M	0.873 - 0.890
Polyphenylene Sulfide	PPS	1.075 - 1.109

5.2.8. Injection Speed

Injection speed is the linear maximum speed of the screw which the machine is capable of during injection, expressed in cm/s.

Injection speed affects the injection time. Moulding of thin-walled articles requires high injection speed so that the melt does not solidify before the cavity is completely filled. Some machines have multiple injection speeds available during injection for this purpose.

5.2.9. Injection Rate

As an alternative to injection speed, some PIMM specifications use injection rate. Injection rate is the maximum volume swept out by the screw per second during injection. It is expressed in cm^3/s. Calculation of injection rate is as follows [31]:

$$IR = \frac{\pi * d_{screw}^{2} * IS}{4} \qquad (5.7)$$

where IR is the injection rate (cm^3/s) and IS is the injection speed (cm/s). Note that, injection speed is not dependent on screw diameter, but injection rate is.

5.2.10. Plasticizing Capacity

Plasticizing capacity is the amount of PS which a PIMM can uniformly plasticize, or raise to a uniform moulding temperature in one hour, at maximum screw rotary speed and zero back pressure. Since it is rated in PS which is an amorphous material, a higher plasticizing capacity is needed for semi-crystalline materials. Although the barrel heaters also contribute to melt the plastic, their capacities are not counted in plasticizing capacity.

Since cycle time is longer than screw rotation time, the shot weight of a machine and its plasticizing capacity set a lower limit on minimum cycle time as follows [31,32]:

$$CT_{\min} = \frac{S_{machine}}{PC_{machine}} \qquad (5.9)$$

where CT_{min} is minimum cycle time (s) and $PC_{machine}$ plasticizing capacity of the machine (g/s). It is particularly important to match shot weight and plasticizing capacity in the case of fast cycling machines producing thin walled or close tolerance components. Plasticizing capacity could be increased by a larger electric motor and hydraulic pump.

5.2.11. Screw Rotary Speed

Screw rotary speed is specified as a range in rpm. Screw rotary speed by itself is not as critical as screw surface speed. The two are related by the screw diameter, as follows [31]:

$$SSS = \frac{\pi * d_{screw} * SRS}{60} \tag{5.8}$$

where SSS is the screw surface speed (cm/s) and SRS is the screw rotary speed (rpm).

Table 5.3. Optimum and Maximum Surface Speed of Resins [31].

Abbreviation	Optimum surface speed (mm/s)	Maximum surface speed (mm/s)
GPPS (PS)	800	950
HIPS	850	900
ABS	550	650
AS (SAN)	400	450
LDPE	700	750
HDPE	750	800
PP	750	850
PPVC	150	200
UPVC	150	200
PA-6	400	500
PA-66	400	500
PMMA	350	400
PC	400	500
POM (Copolymer)	200	500
POM (Homopolymer)	100	300
PET	300	400
PBT	300	350
CA	400	500
PPO-M	400	500
PPS	200	300

Table 5.3 shows optimum and maximum surface speeds of several resins. Each plastic material has a recommended maximum screw surface speed which must not be exceeded.

5.3. CLAMPING UNIT ATTRIBUTES

5.3.1. Clamping Force

Clamping force (tonnage) is an important attribute of the clamping unit of a PIMM. It is the maximum force which the machine is capable of to keep the mould closed against the cavity pressure during injection. Insufficient clamping force gives rise to flash at the mould joint. Most PIMMs today use their clamping force in their model name, e.g. ME125II. Here, "125" means that the clamping tonnage of this machine is 125 tonnes.

It is advisable to use a sufficient clamping force below the maximum limit. The sufficient clamping force is proportional to the projected area of the cavity (preform). Projected cavity area is the cavity area projected onto the plane at the mould parting surface.

The clamping force needed could be estimated in several ways. The conservative method is to multiply the projected cavity area by a constant which is different for each material, as follows [31]:

$$CF_{resin} = A_{preform} * Q * CFE_{max} \tag{5.10}$$

where CF_{resin} is the clamping force capacity of resin (tonnes), $A_{preform}$ is the projected area of one preform (cm^2), Q is the number of cavities, and CFE_{max} is the maximum clamping force estimation ($tonnes/cm^2$).

Table 5.4 lists the constants for commonly used resins. The projected area of one preform is calculated by [31]:

$$A_{preform} = \frac{\pi * d_{screw}^2}{4} \tag{5.11}$$

Table 5.4. Simple Clamping Force Estimation [31].

Resin	tonnes/in^2	tonnes/cm^2	MN/m^2
PS (GPPS)	1.0 - 2.0	0.155 - 0.31	15.4 - 30.9
PS (GPPS) (thin walls)	3.0 - 4.0	0.465 - 0.62	46.3 - 61.8
HIPS	1.0 - 2.0	0.155 - 0.31	15.4 - 30.9
HIPS (thin walls)	2.5 - 3.5	0.388 - 0.543	38.6 - 54.0
ABS	2.5 - 4.0	0.388 - 0.62	38.6 - 61.8
AS (SAN)	2.5 - 3.0	0.388 - 0.465	38.6 - 46.3
AS (SAN) (long flows)	3.0 - 4.0	0.465 - 0.62	46.3 - 61.8
LDPE	1.0 - 2.0	0.155 - 0.31	15.4 - 30.9
HDPE	1.5 - 2.5	0.233 - 0.388	23.2 - 38.6
HDPE (long flows)	2.5 - 3.5	0.388 - 0.543	38.6 - 54.0
PP (Homo/Copolymer)	1.5 - 2.5	0.233 - 0.388	23.3 - 38.6
PP (H/Co) (long flows)	2.5 - 3.5	0.388 - 0.543	38.6 - 54.0
PPVC	1.5 - 2.5	0.233 - 0.388	23.3 - 38.6
UPVC	2.0 - 3.0	0.31 - 0.465	30.9 - 46.3
PA6, PA66	4.0 - 5.0	0.62 - 0.775	61.8 - 77.2
PMMA	2.0 - 4.0	0.31 - 0.62	30.9 - 61.8
PC	3.0 - 5.0	0.465 - 0.775	46.3 - 77.2
POM (Homo/Copolymer)	3.0 - 5.0	0.465 - 0.775	46.3 - 77.2
PET (Amorphous)	2.0 - 2.5	0.31 - 0.388	30.9 - 38.6
PET (Crystalline)	4.0 - 6.0	0.62 - 0.93	61.8 - 92.6
PBT	3.0 - 4.0	0.465 - 0.62	46.3 - 61.8
CA	1.0 - 2.0	0.155 - 0.31	15.4 - 30.9
PPO-M (unreinforced)	2.0 - 3.0	0.31 - 0.465	30.9 - 46.3
PPO-M (reinforced)	4.0 - 5.0	0.62 - 0.775	61.8 - 77.2
PPS	2.0 - 3.0	0.31 - 0.465	30.9 - 46.3

The calculation above has not accounted for viscosity. In other words, above calculation is considered to be correct for the viscosity factor of GPPS which is 1.0. However, the most accurate calculation is the multiplication of calculated value of clamping tonnage with the viscosity factor of the resin [31]:

$$CF_{machine} = VF_{resin} * CF_{resin} \qquad (5.12)$$

where $CF_{machine}$ is the clamping tonnage of the machine (tonnes) and VF_{resin} is the viscosity factor for the resin.

Viscosity factors for common resins are listed in Table 5.5.

Table 5.5. Viscosity Factor [31].

Thermoplastics	Viscosity factor
GPPS (PS)	1
PP	1 - 1.2
PE	1 - 1.3
Nylons (PA6 or PA66), POM	1.2 - 1.4
Cellulosics	1.3 - 1.5
ABS, ASA, SAN	1.3 - 1.5
PMMA	1.5 - 1.7
PC, PES, PSU	1.7 - 2.0
PVC	2

5.3.2. Mould Opening Stroke

Mould opening stroke is the displacement of the moving platen from mould close to mould open. Mould opening stroke determines the maximum height of the moulded part the machine is capable of handling. The relationship is as follows [31]:

$$MOS \geq 2 * MH_{max} + SL \tag{5.13}$$

where MOS is the mould opening stroke (cm), MH_{max} is the maximum mould height (cm) and SL is the sprue length (cm). Figure 5.1 shows the terminology for the mould opening stroke. Note that, in a hot runner system, sprue length is neglected. The inequality allows for a clearance for gravity, the robot arm or human hand to remove the part.

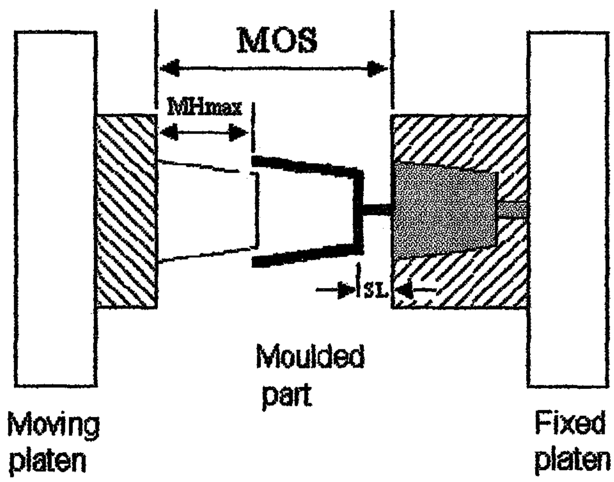

Figure 5.1. Mould Opening Stroke.

5.3.3. Mould Height or Thickness

In a toggle clamp PIMM specification, mould height is expressed as a range, from the minimum to the maximum mould height that the machine could accommodate. The difference is the mould height adjustment that the machine is capable of. In a direct hydraulic clamp PIMM specification, mould height is expressed as a number specifying the minimum mould height that the machine could accommodate.

The actual mould height must be bigger than the machine's minimum mould height so that the mould is to be closed and clamped. Otherwise, a smaller machine (i.e., a machine having smaller clamping unit) is called for. On the other hand, the actual mould height must be less than the machine's maximum mould height so that the mould is to be fit in. Otherwise, a bigger machine is called for.

5.3.4. Maximum (Platen) Daylight

It is the maximum opening between fixed and moving platens when the clamp is wide open. It is related to mould opening stroke and minimum/maximum mould height as follows [31]:

- For a toggle clamp machine:

$$PD = MOS + MH_{max} \tag{5.14.a}$$

- For a direct hydraulic clamp machine:

$$PD = MOS + MH_{min} \tag{5.14.b}$$

where PD is the maximum (platen) daylight (cm), MH_{max} and MH_{min} are the maximum and minimum mould heights (cm).

5.3.5. Space Between Tiebars

The mould must fit within the space between tiebars. This space is expressed in horizontal and vertical dimensions as shown in Figure 5.2.

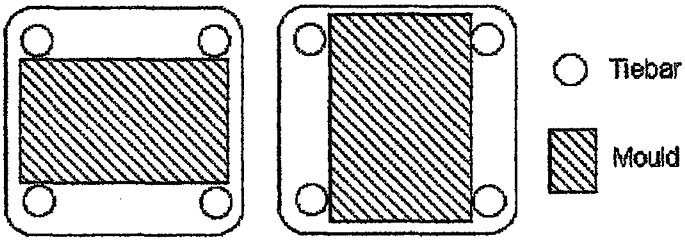

Figure 5.2. Space Between Tiebars.

It is advised that there is a clearance of 25 mm on each side between mould and tiebars for a small mould and 50 mm for a big mould [31]. This is to avoid destruction of the heavy mould against the tiebars during loading, and subsequently affecting the bearing in the moving platen which travels over them. "Tiebarless PIMMs" do not have this restriction.

5.3.6. Platen Thickness

The moving and fixed platens must have sufficient stiffness to transmit the forces of the tiebars to the mould with minimum deflection. For a given geometry, a flat platen's deflection is proportional to the cube of its thickness. Especially for the moving platen, a compromise has to be obtained between weight and thickness.

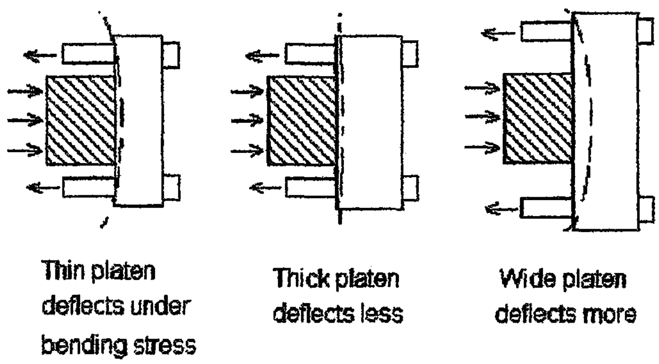

Figure 5.3. Platen Deflection is Affected by Platen Thickness and Size.

Space between tiebars is related to platen size [31]. If this space is increased without increasing the platen thickness, the platen under the same load deflects more. Therefore, space between tiebars must be considered alone, but must be checked against platen stiffness. Platen deflection causes the mould to deflect which causes a change in the shape and dimensions of the moulded article (see Figure 5.3).

5.4. GENERAL ATTRIBUTES

5.4.1. EUROMAP Size Rating

European Committee of Machinery Manufacturers for Plastics and Rubber Industries (EUROMAP) size rating is a standard way for specifying the size of the clamping unit and the injection unit of a machine. It publishes a number of recommendations.

The rating is made up of two numbers: "xxx-yyy". "xxx" is the clamping force of the clamping unit in kN. "yyy" is the product of injection pressure in kbar and injection volume in cm^3. Hence, "xxx" is the rating of the clamping unit and "yyy" is that of the injection unit. For a given injection unit, "yyy" is constant with respect to the choice of screw diameter.

Some manufacturers provides several injection units for a machine of a certain clamping force. The different injection units are specified by their "yyy" rating. The higher is "yyy", the more powerful is the injection unit.

5.4.2. International Size Rating

In the Far East where kN and kbar are less well-known than tonne and kg/cm^2, an alternative size rating is used instead of EUROMAP. International Size Rating is made up of two numbers: "aaa/bbb". "aaa" is the product of injection pressure in kg/cm^2 and injection volume in cm^3 divided by 1000. "bbb" is the clamping force of the clamping unit in tonnes. Note that, the sequence of two numbers are reversed from those in the EUROMAP counterpart.

5.4.3. Cycle Time

Cycle time is the sum of mould closing time, injection time, cooling time and mould opening time. Cooling time is not a PIMM attribute as a mould and moulded part attribute. Cycle time is to be as short as possible without affecting the ejection rate of the moulded parts and the long-term reliability of the machine. A sample break-down of a complete injection moulding cycle is shown in Figure 5.4.

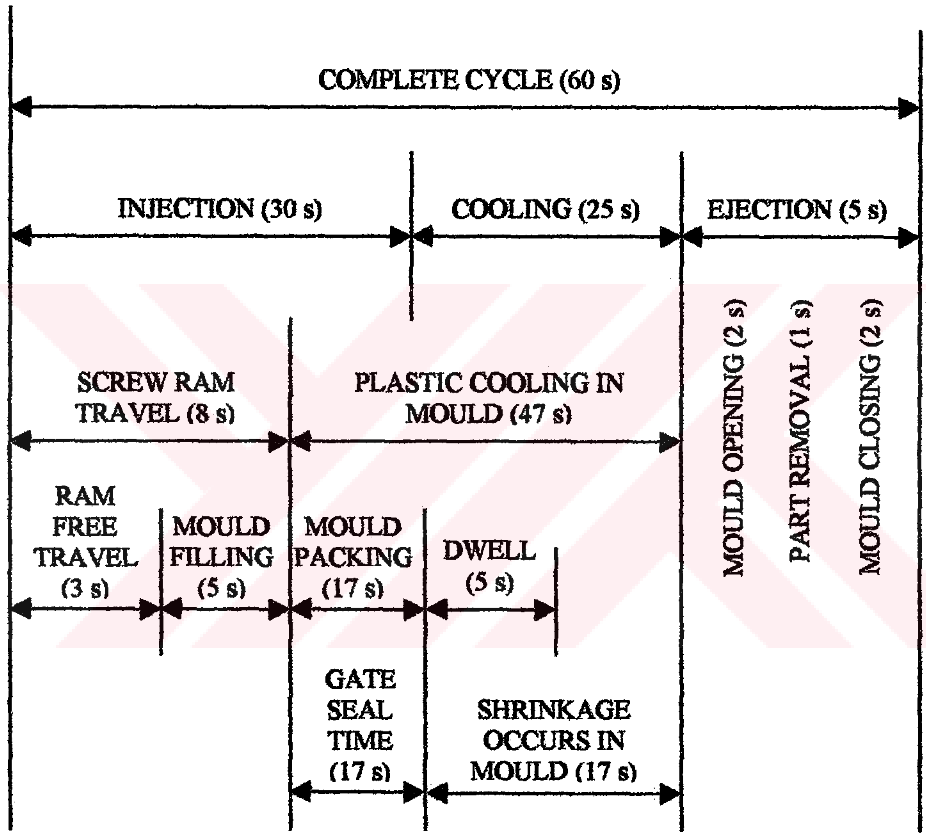

Figure 5.4. A Break-Down of a Complete Injection Moulding Cycle [20].

5.4.4. Dry Cycle Time

Dry cycle time is the combination of mould closing time, mould opening time, and idle time. Dry cycle time is the ultimate cycle time as there is no cooling period. An alternative expression is cycle rate which is the number of cycles per minute. Running a machine at the maximum possible cycle rate is not desirable if the machine is not running smooth and stable.

5.4.5. Electric Motor Rating

The hydraulic system is driven by an electric motor. It converts electrical energy to mechanical energy at a certain efficiency. An electrical motor is rated in terms of kW or HP which denotes its maximum power delivery under the specified conditions. Some manufacturers offer a bigger pump size as an alternative. The motor size is also increased.

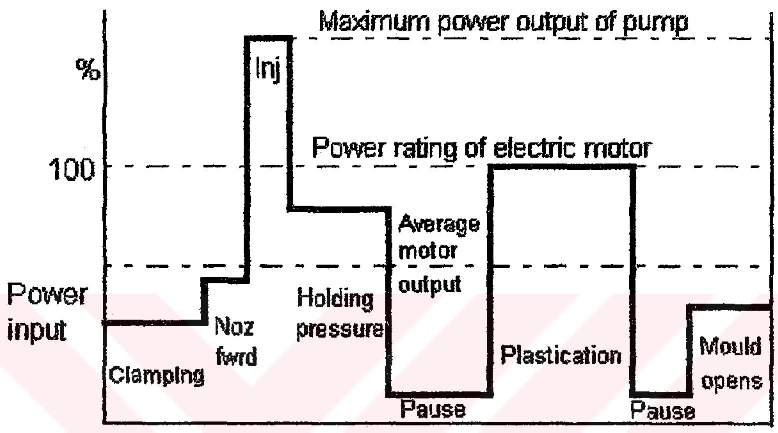

Figure 5.5. Power Demand During the Moulding Cycle [31].

The moulding cycle demands widely varying hydraulic power in its different phases (Figure 5.5). At the electric motor, this translates to a similar demand in electrical power. Usually, the injection phase is the most demanding phase of the cycle. An electric motor is rated at below that power, requiring it to run above its rating in the injection phase.

5.4.6. Electric Heater Rating

Electric band heaters along the barrel provides the initial heat up to the resin at start up. It also supplements the heating by plastication (when the screw rotates) during the moulding cycle. A higher rating per heater has the advantage of shortening the initial heat up time. Usually, there is one to two band heaters per heating zone. The heaters are evenly distributed among the three phases as much as possible.

5.4.7. Total Power

This equals the combination of electric motor rating and electric heater rating. It is for planning the current in the electric power connection. However, motor overloading is not accounted for in total power as the motor rating is used.

5.4.8. Oil Tank Capacity

Oil tank capacity has significance in cooling and number of barrels of oil to purchase. More oil in a bigger tank reduces the temperature of the oil since the heat generated is spread out more. Furthermore, a bigger tank has a bigger cooling surface.

5.4.9. Hopper Capacity

A bigger hopper capacity requires less attention by the operator. However, when moulding hygroscopic resin, a hopper must not be filled for the resin to remain in the hopper for more than an hour. The capacity of hopper can be found as [31]:

$$HC = \frac{S_{resin(actual)}}{CT} \tag{5.15}$$

where HC is the hopper capacity (g), CT is cycle time (s) and $S_{resin(actual)}$ is the actual shot weight of the resin (g).

5.5. CONCLUSION

The parameters explained in foregoing sections affect the selection of a PIMM. They are also affecting the selection of a thermoplastic resin. Therefore, determination of these parameters requires a great experience and knowledge about machine and material specifications. Chapters 6 and 7 use the equations above for the selection of best machine(s) and material(s), and also the optimum number of cavities.

CHAPTER VI

EXPERT SYSTEM FOR PLASTIC INJECTION MOULDING MACHINES (EX-PIMM)

6.1. INTRODUCTION

This chapter describes the developed system in this study. The structure and the logic of the system are explained in detail. There are three modules in the developed system, and the most important stages of each module are represented in the following sections. Section 6.2 introduces the most important properties of the EX-PIMM. Section 6.3 covers the algorithm used in the selection of a Plastic Injection Moulding Machine (PIMM). Section 6.4 discusses the algorithm used in the selection of a thermoplastic resin. Section 6.5 deals with the determination of optimum number of cavities. Section 6.6 includes concluding remarks.

6.2. DESCRIPTION OF THE EX-PIMM

The system developed in this study is called "EXpert System for Plastic Injection Moulding Machines (EX-PIMM)". The developed system consists of three modules:

1. Selection of a Plastic Injection Moulding Machine **(Module-1)**.
2. Selection of a thermoplastic resin **(Module-2)**.
3. Determination of optimum number of cavities **(Module-3)**.

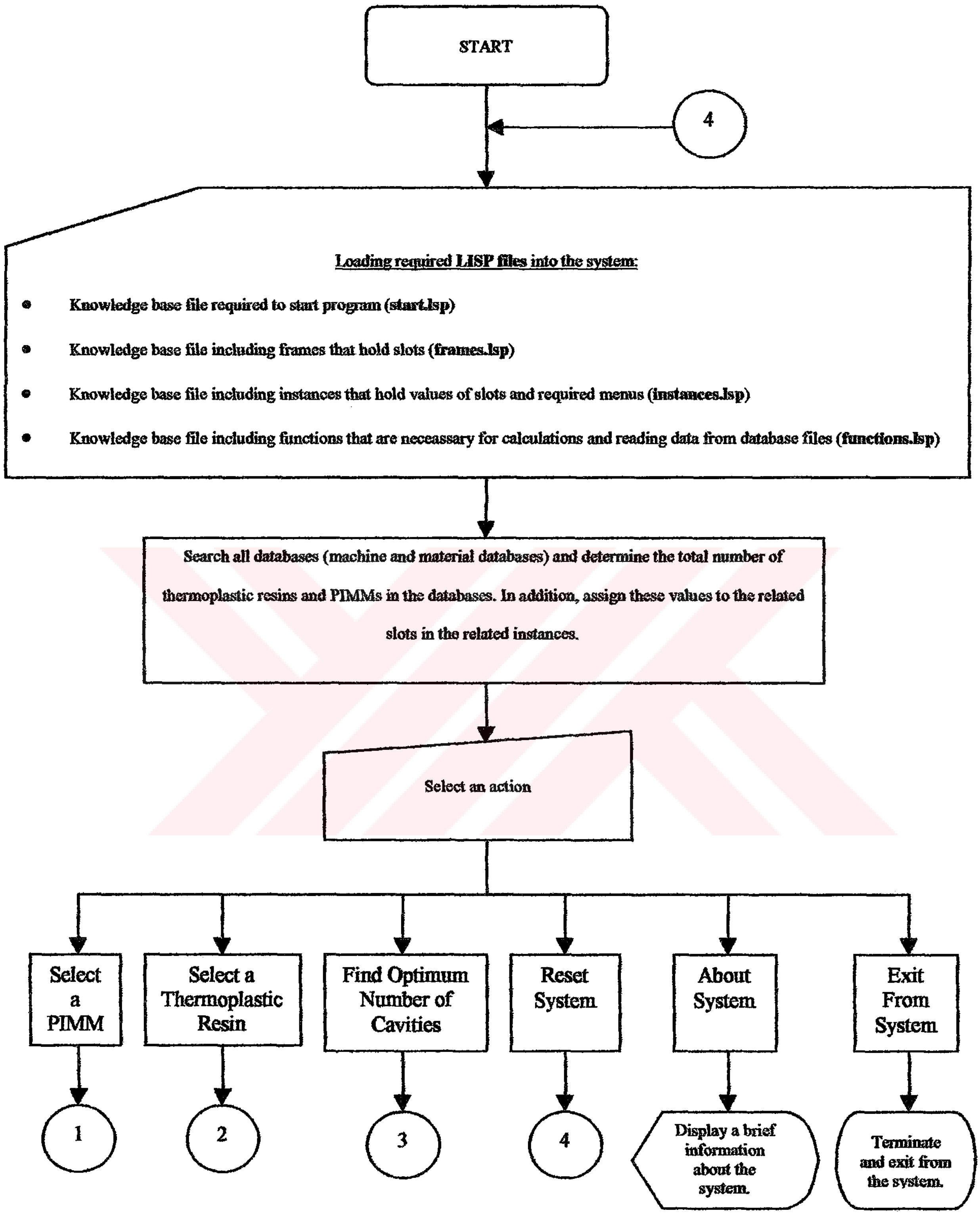

Figure 6.1. Flowchart for the EX-PIMM.

Each module has its own rule base or knowledge base file including forward and backward type of rules. Each module uses only its knowledge base file during run-time. However, the developed expert system is able to manage these three modules interactively. In other words, when one module is running, some necessary information or rules required during run-time can be obtained from knowledge base files of other modules without loading them into the memory. Therefore, the developed system reduces the computation time and provides a network relationship between all knowledge base files. Figure 6.1 shows the general flowchart of the EX-PIMM.

At the beginning of the program, before running a module, the system loads some knowledge base files into the memory. These files are [33]:

- **start.lsp** (knowledge base file required to start program and load other necessary files)
- **frames.lsp** (knowledge base file including frames that hold necessary slots)
- **instances.lsp** (knowledge base file including required menus and instances holding values of slots)
- **functions.lsp** (knowledge base file containing functions necessary for calculations and reading data from database files)

In addition to these files, system loads some necessary interfaces, such as:

- **Dynamic Graphic Interface** [34] (the interface providing graphic facility for the menus and bottons of the system)
- **Lotus 1-2-3 Interface** [35] (the interface managing the Lotus 1-2-3 files for reading/writing data from/to database files)

All modules require these knowledge base files and interfaces for calculations, functions, displaying results to the screen, etc. Therefore, these files remain in the memory permanently. However, since they do not have any effect during run-time, they do not occupy any space in the memory. According to purpose of the end-user, knowledge base file of the selected module will be loaded to the memory. In other words, all modules are independent from each other during run-time.

In the developed system, some miscellaneous facilities are available [33]:

- **Reset System** (function for unloading all files from the system, refreshing memory, and loading all necessary files into the system)
- **About System** (menu for displaying a brief information about the system)
- **Exit System** (function for unloading all files from the system and terminating the program)

The detailed information about modules and their flowcharts are included in the following sections.

6.3. MODULE-1: SELECTION OF A PLASTIC INJECTION MOULDING MACHINE

In this module, a Plastic Injection Moulding Machine (PIMM) is selected according the given inputs. There are totally 623 PIMMs in the machine database. All feasible machines satisfying the requirement of end-user could be obtained by this module. In addition, the best one among these feasible machines can also be found by means of an award facility.

Forward Chaining (FC) method is used in this module. In FC method, all knowledge base file should be searched for the solution. Therefore, this module is slower than the third module (i.e., determination of optimum number of cavities). The flowchart of this module is shown in Figure 6.2.

The most important outlines of this module can be expressed as follows:

1. The knowledge base file including rules and assertions related to this module is loaded to the system.

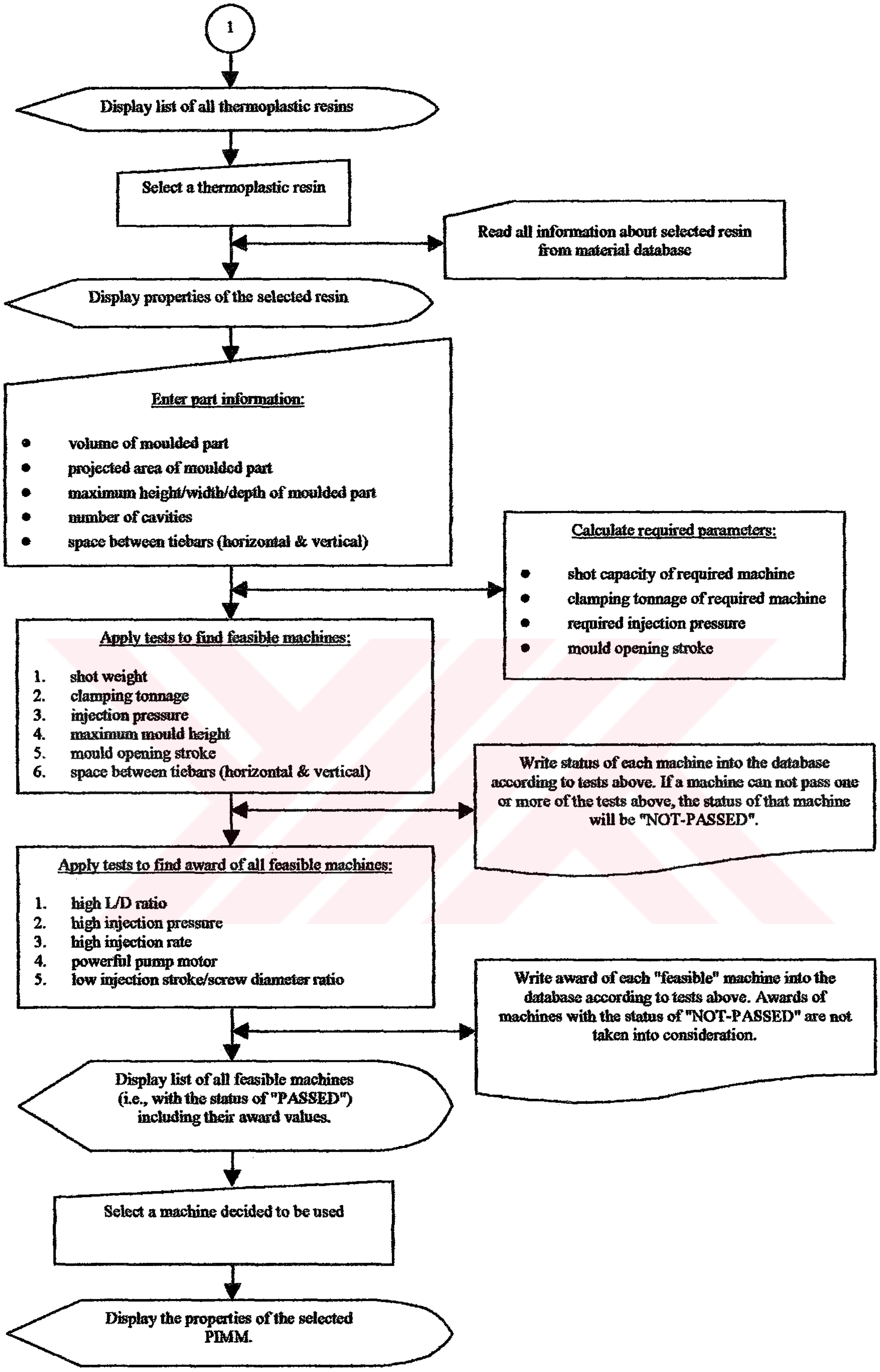

Figure 6.2. Flowchart for the Selection of a PIMM.

2. A thermoplastic resin is selected by the end-user from the material database, and the properties of the selected resin are displayed on the screen.

3. Part and cavity information are entered by the end-user to the system. These are:

- Volume of moulded part (V_{part}) in cm^3
- Projected area of moulded part (A_{part}) in cm^2
- Maximum height/width/depth of moulded part (MH_{max}) in cm
- Number of cavities (Q)
- Horizontal and vertical space between tiebars (SBT_{hor} and SBT_{ver}) in cm

4. Calculate required parameters, as follows:

- Mass of moulded part (M_{part}) in g can be evaluated by:

$$M_{part} = \rho_{resin} * V_{part} \tag{6.1}$$

where ρ_{resin} is the density of the resin (g/cm^3) found in material database.

- Shot weight of moulded part in terms of the selected resin (S_{resin}) is found as:

$$S_{resin} = \frac{Q * M_{part} * SG_{PS}}{SG_{resin} * 0.8} \tag{6.2}$$

where SG_{PS} is the Specific Gravity (S.G.) of the PS and SG_{resin} is the SG of the resin. "0.8" is from "80% rule" to find actual value.

- Clamping force capacity of the selected resin (CF_{resin}) is found as:

$$CF_{resin} = Q * A_{part} * CFE_{max} * VF_{resin} \tag{6.3}$$

where CFE_{max} is the maximum clamping force estimation ($tonnes/cm^2$) from Table 5.4 and VFresin is the viscosity factor of the resin from Table 5.5.

- Injection pressure of the selected resin (IP_{resin}) is already obtained from material database.

- Maximum mould height (MH_{max}) is already entered by the end-user.

- Mould opening stroke (MOS) is calculated as:

$$MOS = 2 * MH_{max} + SL \tag{6.4}$$

where SL is the sprue length (cm). Note that, SL is assumed to be zero in this study.

5. At this stage, some tests are applied to the machines to find feasible machines. There are six tests, and at the end of each test, the "test status" of each machine is written to the database file simultaneously. These tests are as follows:

- $S_{machine}$ must be equal to or greater than S_{resin}.
- $CF_{machine}$ must be equal to or greater than CF_{resin}.
- $IP_{machine}$ must be equal to or greater than IP_{resin}.
- MH_{max} of the machine must be equal to or greater than value entered by the end-user.
- MOS of machine must be equal to or greater than calculated value of MOS.
- SBT_{hor} and SBT_{ver} of the machine must be equal to or greater than values entered by the end-user.

6. After all these tests are completed, "test status" of each machine is written to the related database file and this database file is saved with the name of "test-mac.wk1". This database file includes the test status of all machines.

7. At this stage, some tests are applied to all feasible machines in order to define award value of each feasible machine. A special function is used for the determination of award values. There are five tests, and at the end of each test,

the "award value" of each feasible machine is written to the database file simultaneously. These tests are as follows:

- Give an award to the machine having the highest value of LD.
- Give an award to the machine having the highest value of IP.
- Give an award to the machine having the highest value of IR.
- Give an award to the machine having the highest value of P_{pump}.
- Give an award to the machine having the lowest value of SD.

8. After all these tests are completed, "award value" of each feasible machine is written to the related database file and this database file is saved with the name of "feas-mac.wk1". This database file includes test status and award values of only feasible machines.

9. At this stage, the list of all feasible machines including the award value of each feasible machine is created (read) from "feas-mac.wk1" and displayed to the screen. The best machine is displayed on the top of the list.

10. The end-user selects a machine that is decided to be used, and the properties of the selected machine are displayed to the screen. Note that, this list is created from a database file, and this file can be used independent from the system for other applications in the future.

6.4. MODULE-2: SELECTION OF A THERMOPLASTIC RESIN

This module is similar to the previous module. In this module, a thermoplastic resin is selected according to the given inputs. There are totally 27 thermoplastic resins in the material database. All feasible resins satisfying the requirement of end-user could be obtained by this module. In addition, the best one among these feasible resins can also be found by means of an award facility.

As in the case of previous module, Forward Chaining (FC) method is also used in this module. Therefore, this module is slower than the third module (i.e., determination of optimum number of cavities). The flowchart of this module is shown in Figure 6.3.

The most important stages of this module can be expressed as follows:

1. The knowledge base file including rules and assertions related to this module is loaded to the system.

2. A PIMM is selected by the end-user from the machine database, and the properties of the selected machine are displayed on the screen.

3. Part and cavity information are entered by the end-user to the system. These are:

   - Volume of moulded part (V_{part}) in cm^3
   - Projected area of moulded part (A_{part}) in cm^2
   - Maximum height/width/depth of moulded part (MH_{max}) in cm
   - Number of cavities (Q)

4. Calculate required parameters, as follows:

   - Density to S.G. ratio of required resin (ρ_{resin}/SG_{resin}) can be evaluated by:

$$\frac{\rho_{resin}}{SG_{resin}} = \frac{S_{resin} * 0.8}{SG_{PS} * Q * V_{part}} \tag{6.5}$$

where "0.8" is from "80% rule" to find actual value.

   - Multiplication of maximum clamping force estimation and viscosity factor (CFE_{resin} * VF_{resin}) is found as follows:

$$CFE_{resin(max)} * VF_{resin} = \frac{CF_{resin}}{Q * A_{part}} \tag{6.6}$$

- Injection pressure capacity of the selected machine ($IP_{machine}$) is already obtained from machine database.

5. At this stage, some tests are applied to the resins to find feasible resins. There are three tests, and at the end of each test, the "test status" of each resin is written to the database file simultaneously. These tests are as follows:

   - ρ_{resin}/SG_{resin} (read from database) must be equal to or less than value calculated from equation 6.5.
   - $CFE_{resin(max)}$ * VF_{resin} (read from database) must be equal to or less than value calculated from equation 6.6.
   - IP_{resin} (read from database) must be equal to or less than $IP_{machine}$.

6. After all these tests are completed, "test status" of each resin is written to the related database file and this database file is saved with the name of "test-mat.wk1". This database file includes the test status of all resins.

7. At this stage, some tests are applied to all feasible resins in order to define award value of each feasible resin. A special function is used for the determination of award values. There are three tests, and at the end of each test, the "award value" of each feasible resin is written to the database file simultaneously. These tests are as follows:

   - Give an award to the resin having the lowest value of ρ/SG.
   - Give an award to the resin having the lowest value of CFE_{max}*VF.
   - Give an award to the resin having the lowest value of IP.

8. After all these tests are completed, "award value" of each feasible resin is written to the related database file and this database file is saved with the name of "feas-mat.wk1". This database file includes test status and award values of only feasible resins.

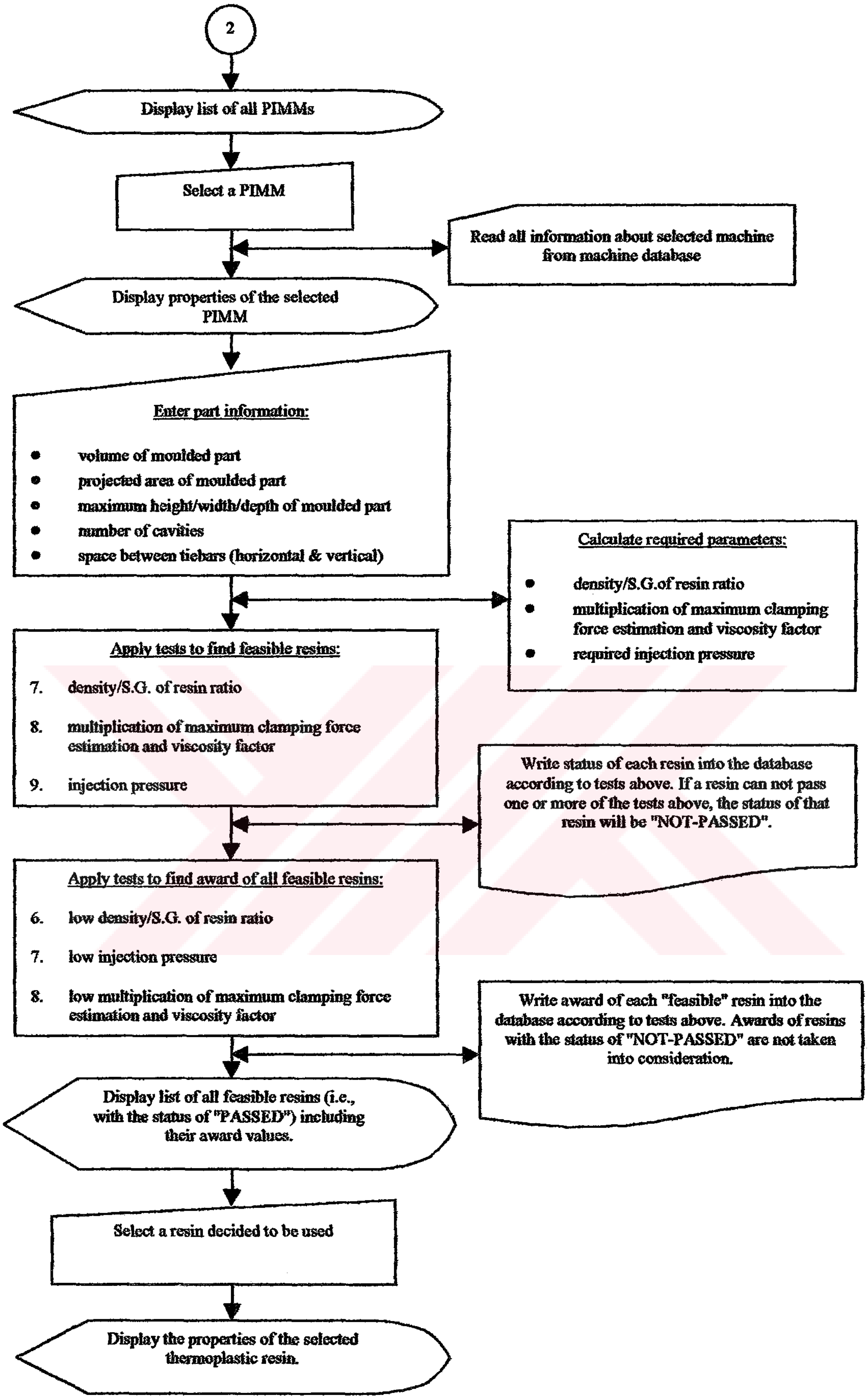

Figure 6.3. Flowchart for the Selection of a Resin.

9. At this stage, the list of all feasible resins including the award value of each feasible resin is created (read) from "feas-mat.wk1" and displayed to the screen. The best resin is displayed on the top of the list.

10. The end-user selects a resin that is decided to be used, and the properties of the selected resin are displayed to the screen. Note that, this list is created from a database file, and this file can be used independent from the system for other applications in the future.

6.5. MODULE-3: DETERMINATION OF THE OPTIMUM NUMBER OF CAVITIES

This module is different from the previous modules. In this module, the optimum number of cavities is determined according to user requirements. This module can be considered as the combination of the previous modules. The flowchart of this module is shown in Figure 6.4.

This module is different from other modules with respect to the methodolgy used. This module uses a Goal-Directed Backward Chaining (GD-BC) as the methodology, whereas other modules use Forward Chaining (FC). In GD-BC method, first of all, all rules and rule sets are searched in all knowledge base files, and then, the definition of the problem is determined by means of backward rules. After that, only required part of the whole knowledge base file is used to solve the problem. In other words, in contrast to other modules, only required part of the memory is consumed during run-time. Therefore, this module is more reliable and faster compared to other modules for this reason.

The most important steps of this module can be expressed as follows:

1. The knowledge base file including rules and assertions related to this module is loaded to the system.

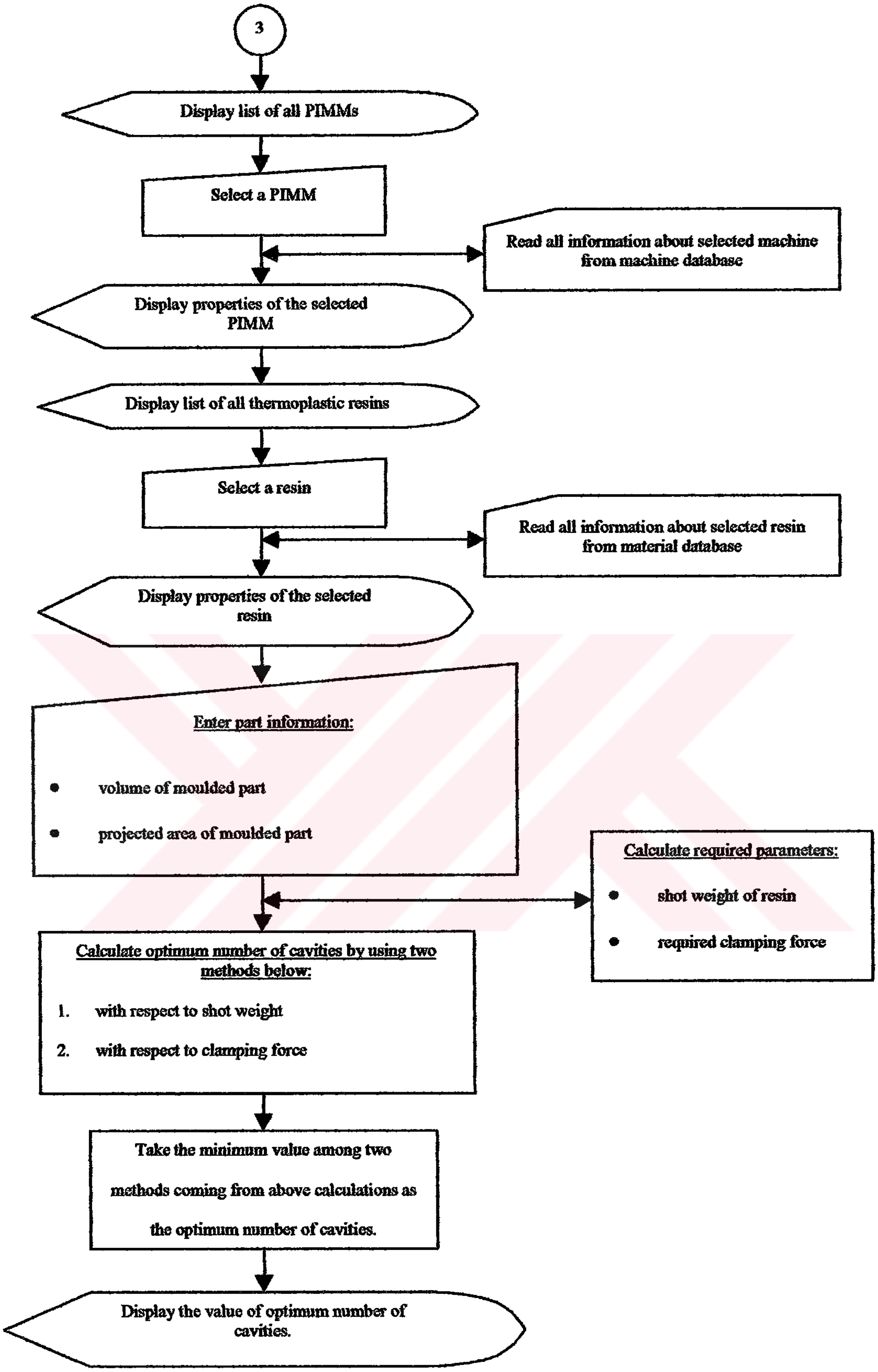

Figure 6.4. Flowchart for the Determination of Optimum Number of Cavities.

2. A PIMM is selected by the end-user from the machine database, and the properties of the selected machine are displayed on the screen.

3. A thermoplastic resin is selected by the end-user from the material database, and the properties of the selected material are displayed on the screen.

4. Part and cavity information are entered by the end-user to the system. These are:

   - Volume of moulded part (V_{part}) in cm^3
   - Projected area of moulded part (A_{part}) in cm^2

5. At this stage, two different values of number of cavities are obtained from the following equations [31,32]:

   - Determination of number of cavities according to shot capacity of the selected machine (Q_1):

$$Q_1 = \frac{S_{machine} * 0.8 * SG_{re\sin}}{SG_{PS} * \rho_{re\sin} * V_{part}} \tag{6.7}$$

   where "0.8" is from "80% rule" to find actual value.

   - Determination of number of cavities according to clamping tonnage of the selected machine (Q_2):

$$Q_2 = \frac{CF_{machine}}{Q * A_{part} * CFE_{re\sin(\max)} * VF_{re\sin}} \tag{6.8}$$

6. The optimum number of cavities (Q_{opt}) is the minimum of the two values obtained previously (Q_1 and Q_2), as follows:

$$Q_{opt} = \min(Q_1, Q_2) \tag{6.9}$$

7. Finally, this optimum value is displayed to the screen for the selected PIMM and thermoplastic resin.

6.6. CONCLUSION

Some lack of information in the database files could be completed by using equations included in chapters 5 and 6. Therefore, before loading the database files to the system, misinformations and errors in those database files must be eliminated so that the system reaches to solutions effectively and quickly. An example problem covering all modules of the system is included in the next chapter.

CHAPTER VII

AN EXAMPLE FOR EX-PIMM

7.1. INTRODUCTION

The methodology and algorithm used in EX-PIMM have been discussed in the previous chapter. An example for three modules of the system is included in this chapter. Section 7.2 includes an example for the selection of a Plastic Injection Moulding Machine (PIMM). Section 7.3 covers the selection of a thermoplastic resin. Finally, Section 7.4 is the determination of the optimum number of cavities. Conclusions and discussions are included in Section 7.5.

7.2. MODULE-1: SELECTION OF A PIMM

Assume that a moulder is making Crystalline Polyethylene Terephthalate (PET-C) preforms. Each preform has the following specifications:

- Volume of each preform ($V_{preform}$) is 10.95 cm^3.
- Projected area of each preform ($A_{preform}$) is 8.815 cm^2.
- Maximum height/depth/width of each preform (MH_{max}) is 10.35 cm.
- There are four cavities per mould (Q).
- Required space between tiebars (SBT_{hor} x SBT_{ver}) are 310 x 310 mm.

Table 7.1. Choosing from Three 50-ton Models.

Machine brand	Brand A			Brand B			Brand C		
International size rating	137/56			181/54			198/50		
Screw Type	A	B	C	A	B	C	A	B	C
Screw diameter (mm)	25	28	31	30	33	36	28	30	32
Screw L/D ratio	22	19	17	22	20	18			
Theoretical injection volume (cm^3)	63	80	98	84.8	102.6	122.1	92	106	120
Shot weight in PS (g)	55	69	85	71.3	86.2	102.6	82	95	108
Injection pressure (bar)	2150	1715	1400	2133	1763	1481	2142	1866	1640
Plasticizing capacity (g/s)	5	6.4	8.1				6.4	7.2	8.3
Injection rate (cm^3/s)				78	94	120	58	67	76
Injection stroke (mm)	130	130	130	120	120	120			
Injection stroke / screw diameter	5.2	4.64	4.19	4	3.64	3.33	5.36	5	4.69
Clamping method	Toggle			Direct Hydraulic			Toggle		
Clamping force (tonnes)	56			54			50		
Space between tiebars (mm)	310x310			320x320			305x220		
Platen daylight (mm)	540			550			530		
Mould opening stroke (mm)	220			400			220		
Max. mould height (mm)	320						310		
Min. mould height (mm)	80			120			75		
Dry cycle time (sec)	0.625								
Installed driving power (kW)	7.5			11			7.5		
Installed total power (kW)	12.3						11.1		
Oil tank capacity (litre)	150						180		
Hopper capacity (litre)	31								

A simple pipe adapter is used as an example part. This sample part has the above specifications. Shape of the sample part is shown in Figure 7.1. The selection is narrowed down to three machines from three different manufacturers. The machine specifications are shown in Table 7.1.

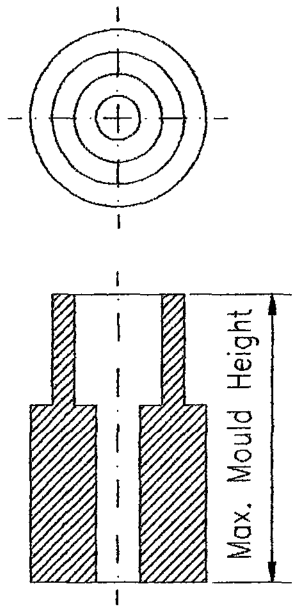

Figure 7.1. A Simple Pipe Adapter.

Note that, the weight and projected area of runners, and sprue length are neglected in this example. In addition, the properties of the resin are taken from tables in the previous chapter. Note that, all parameters are not listed in the table. For example, Brand C does not list screw L/D ratio, Brand B does not list plasticizing capacity. Therefore, comparison is done based on partial information.

7.2.1. Mass of Each Preform

Mass of each preform ($M_{preform}$) is found by:

$$M_{preform} = \rho_{resin} * V_{preform} \qquad (7.1)$$

where ρ_{resin} is 0.685 g/cm³ and $V_{preform}$ is 10.95 cm³. Therefore, mass of one preform is found as approximately 7.5 g.

7.2.2. Shot Weight

PET-C has a Specific Gravity (SG) of 1.35 and SG of Polystyrene (PS) is 1.05. The shot weight of resin in PS (S_{resin}) is equivalent to:

$$S_{resin} = \frac{Q * M_{preform} * SG_{PS}}{SG_{resin} * 0.8} \quad (7.2)$$

where "0.8" is coming from "80% rule". Then, S_{resin} is found to be 29.2 g. From Table 7.1, all screws of machines give sufficient shot weight.

7.2.3. Clamping Force

Maximum Clamping Force Estimation (CFE_{max}) of PET-C is 0.93 tonnes/cm², and Viscosity Factor (VF) of PET-C is 1.15. The clamping force needed is calculated by:

$$C_{machine} = CFE_{max} * A_{preform} * Q * VF_{resin} \quad (7.3)$$

and is equal to 37.7 tonnes. From table 7.1, All three brands are adequate.

7.2.4. Injection Pressure

PET-C needs a high first stage injection pressure of 1600 bars. From Table 7.1, Screw type C of both Brand B and Brand C are eliminated due to insufficient injection pressure. This elimination is shown in Table 7.2.

Table 7.2. Elimination Based on Injection Pressure.

Machine brand	**Brand A**			**Brand B**			**Brand C**		
International size rating	137/56			181/54			198/50		
Screw Type	A	B	C	A	B	C	A	B	C
Screw diameter (mm)	25	28	~~31~~	30	33	~~36~~	28	30	32
Screw L/D ratio	22	19	~~17~~	22	20	~~18~~			
Injection volume (cm^3)	63	80	~~98~~	84.8	102.6	~~122.1~~	92	106	120
Shot weight in PS (g)	55	69	~~85~~	71.3	86.2	~~102.6~~	82	95	108
Injection pressure (kg/cm^2)	2150	1715	~~1400~~	2133	1763	~~1481~~	2142	1866	1640

7.2.5. Maximum Mould Height

Unlike Brand A and Brand C which are toggle clamped, Brand B is a direct hydraulic clamp machine. For such machines, the maximum mould height is usually not specified, but it always equals the maximum platen daylight.

Maximum platen daylight (PD) for Brand B is the sum of Mould Opening Stroke (MOS) and Minimum Mould Height (MH_{min}), as follows:

$$PD = MOS + MH_{min} \tag{7.4}$$

and, from Table 7.1, it is found to be 550 mm.

For machines of similar clamping force, a direct hydraulic clamp machine has a much bigger maximum mould height than a toggle clamp machine. Since the preform is 10.35 cm long, all three machines have sufficient maximum mould height.

7.2.6. Mould Opening Stroke

The PET-C preforms are each 10.35 cm long. Assuming there is no sprue (i.e., SL is zero), the mould opening stroke should be:

$$MOS \geq 2 * MH_{max} + SL \tag{7.5}$$

which is at least 207 mm. All machines are enough for this distance.

7.2.7. Space Between Tiebars

All screws of Brand C are eliminated due to insufficient distance between tiebars. This elimination is shown in Table 7.3.

Table 7.3. Elimination Based on Space Between Tiebars.

Machine brand	Brand A			Brand B			Brand C		
International size rating	137/56			181/54			~~198/50~~		
Screw Type	A	B	C	A	B	C	A	B	C
Screw diameter (mm)	25	28	~~31~~	30	33	~~36~~	~~28~~	~~30~~	~~32~~
Screw L/D ratio	22	19	~~17~~	22	20	~~18~~			
Injection volume (cm^3)	63	80	~~98~~	84.8	102.6	~~122.1~~	~~92~~	~~106~~	~~120~~
Shot weight in PS (g)	55	69	~~85~~	71.3	86.2	~~102.6~~	~~82~~	~~95~~	~~108~~
Injection pressure (bar)	2150	1715	~~1400~~	2133	1763	~~1481~~	~~2142~~	~~1866~~	~~1640~~
Plasticizing capacity (g/s)	5	6.4	~~8.1~~				~~6.4~~	~~7.2~~	~~8.3~~
Injection rate (cm^3/s)				78	94	~~120~~	~~58~~	~~67~~	~~76~~
Injection stroke (mm)	130	130	~~130~~	120	120	~~120~~			
Injection stroke / screw diameter	5.2	4.64	~~4.19~~	4	3.64	~~3.33~~	~~5.36~~	~~5~~	~~4.69~~
Clamping method	Toggle			Direct Hydraulic			~~Toggle~~		
Clamping force (tonnes)	56			54			~~53~~		
Space between tiebars (mm)	310x310			320x320			~~305x220~~		

Up to this stage, due to eliminations, only four machines are satisfactory. Therefore, screw types of A and B of both Brand A and Brand B are the "feasible machines". The following sections are used for obtaining the "best PIMM" among other feasible machines. There are five tests and an award value of 20 points per each test will be given to the best machine(s).

7.2.8. High Screw L/D Ratio

Screw type of A of both Brand A and Brand B have the highest value of screw L/D ratio among others. Therefore, an award value is given to these machines. Note that, award value is divided by two, since there are two best machines for this test. Therefore, each machine takes 10 points as award value.

7.2.9. High Injection Pressure

Screw type of A of Brand A has the highest value of injection pressure. Therefore, an award value of 20 points is given to this machine.

7.2.10. High Injection Rate

Injection rate values are not given in Table 7.1. Since those values can not be found by calculations, none of screw type of Brand A could have an award value. At this stage, only screw type of B of Brand B takes an award of 20 points.

7.2.11. Powerful Pump Motor (Installed Driving Power)

At this stage, all screw types of Brand B are preferred to the other machines due to highest value of pump motor power. Therefore, screw types of A and B of Brand B takes an award value of 10 points.

7.2.12. Low Injection Stroke/Screw Diameter Ratio

High injection stroke/screw diameter ratio takes away the advantages of high L/D ratio. Consequently, the machine having the lowest ratio takes the award value. Screw type of B of Brand B is the best machine at this stage.

7.2.13. The Final Selection

At the end of all tests, award values of each feasible machine are shown in Table 7.4. Screw type of B of Brand B is the clear choice. It has a high injection rate, a low injection stroke/screw diameter ratio, and a powerful electric motor.

Table 7.4. Award Values of Each Feasible Machine.

Name of the test and corresponding award values of each machine	Brand A		Brand B	
	A	B	A	B
High L/D ratio	10	0	10	0
High injection pressure	20	0	0	0
High injection rate	0	0	0	20
Powerful pump motor	0	0	10	10
Low injection stroke / screw diameter ratio	0	0	0	20
TOTAL AWARD VALUE	30	0	20	**50**

7.3. MODULE-2: SELECTION OF A THERMOPLASTIC RESIN

Assume that a moulder has the machine which is the selected PIMM in the previous section and each preform has the following specifications:

- Volume of each preform ($V_{preform}$) is 10.95 cm^3.
- Projected area of each preform ($A_{preform}$) is 8.815 cm^2.
- Maximum height/depth/width of each preform (MH_{max}) is 10.35 cm.
- There are four cavities per mould (Q).

The selection is narrowed down to three resins used in different applications. The resin specifications are shown in Table 7.5. Note that, the weight and projected area of runners, and sprue length are also neglected in this example. In addition, the properties of the selected PIMM are taken from Table 7.1 in the previous section.

Table 7.5. Choosing from Three Resins.

Name of resin	Polystyrene (General Purpose)	Plasticized Polyvinyl Chloride (soft)	Polyethylene Terephthalate (Crystalline)
Abbreviation	PS-GP	PPVC-S	PET-C
Minimum injection pressure (bar)	690	690	
Maximum injection pressure (bar)	1380	1380	1600
Minimum density (g/cm³)		1.38	
Maximum density (g/cm³)	1.05	1.55	1.37
Minimum specific gravity at room temperature	1.04	1.19	1.29
Minimum specific gravity at room temperature	1.09	1.35	1.41
Minimum clamping force estimation (tonnes/cm²)	0.155	0.233	0.62
Maximum clamping force estimation (tonnes/cm²)	0.31	0.388	0.93
Minimum viscosity factor			1
Maximum viscosity factor	1	2	1.3
Optimum surface speed (mm/s)	800	150	300
Maximum surface speed (mm/s)	950	200	400

Note that, all parameters are not listed. For example, PS-GP and PPVC-S do not list minimum viscosity factors, PET-C does not list minimum injection pressure. However, some corrections may be done. For example, minimum density or minimum viscosity is said to be unity when these values are not given. Therefore, comparison is done based on partial information.

7.3.1. Density/Specific Gravity (S.G.) Ratio

This ratio for a resin can be found by:

$$\left(\frac{\rho_{resin}}{SG_{resin}}\right)_{required} = \frac{\dfrac{\rho_{resin(min)} + \rho_{resin(max)}}{2}}{\dfrac{SG_{resin(min)} + SG_{resin(max)}}{2}} \tag{7.6}$$

where values are included in Table 7.5. The required ratio for the selected machine is coming from the shot capacity of that machine:

$$\left(\frac{\rho_{resin}}{SG_{resin}}\right)_{machine} = \frac{S_{machine} * 0.8}{Q * V_{preform} * SG_{PS}} \tag{7.7}$$

where "0.8" is from "80% rule" to find actual value, and SG_{PS} is 1.05. Other required values are known from previous calculations and tables. Then, this ratio is found as 1.499. Therefore, the relation is as follows:

$$\left(\frac{\rho_{resin}}{SG_{resin}}\right)_{required} \leq 1.499$$

From Table 7.5, all resins have smaller value than 1.499, therefore, all of them pass this test.

7.3.2. Multiplication of Maximum Clamping Force Estimation and Viscosity Factor

This multiplication for the selected machine is coming from clamping tonnage of that machine:

$$CFE_{resin(max)} * VF_{resin} = \frac{C_{machine}}{A_{part} * Q} \tag{7.8}$$

From this equation, the multiplication is found to be 1.531. From Table 7.5, all resins have a value less than 1.531. Therefore, all resins are satisfactory for this test.

7.3.3. Maximum Injection Pressure

From Table 7.1, maximum injection pressure of the selected machine is 1763 bars. Maximum injection pressure values of all resins are less than this value. Consequently, none of resins is eliminated at this stage.

Up to this stage, all resins passed all tests. Therefore, all resins are said to be "feasible". The following sections are used for obtaining the "best thermoplastic resin" among other feasible resins. There are three tests and an award value of 33 points per each test will be given to the best resin(s).

7.3.4. Low Density/Specific Gravity (S.G.) Ratio

This ratio for each machine is calculated from Equation 7.6. From Table 7.5, PET-C has the lowest value (0.877) of this ratio among other resins. Therefore, this resin takes an award of 33 points.

7.3.5. Low Multiplication of Maximum Clamping Force Estimation and Viscosity Factor

Viscosity factor (VF) of each resin is found by:

$$VF_{resin} = \frac{VF_{resin(min)} + VF_{resin(max)}}{2} \tag{7.9}$$

From Table 7.5, PS-GP has the lowest value (0.155) of this multiplication among other resins. Therefore, this resin takes an award of 33 points.

7.3.6. Low Maximum Injection Pressure

A machine can inject resins having low maximum injection pressure. As shown in Table 7.5, PS-GP and PPVC-S have the lowest maximum injection pressure value (1380) among other resins. Therefore, each of these resins takes an award of 16.5 points.

7.3.7. The Final Selection

At the end of all tests, award values of each feasible resin are shown in Table 7.6. PS-GP is the best choice. It has a low multiplication of maximum clamping force estimation by viscosity factor, and a low maximum injection pressure.

Table 7.6. Award Values of Each Feasible Resin.

Name of the test and corresponding award values of each resin	PS-GP	PPVC-S	PET-C
Low density/specific gravity ratio	0	0	33
Low multiplication of maximum clamping force estimation and viscosity factor	33	0	0
Low maximum injection pressure	16.5	16.5	0
TOTAL AWARD VALUE	49.5	16.5	33

7.4. MODULE-3: DETERMINATION OF OPTIMUM NUMBER OF CAVITIES

Assume that a moulder has the machine and the resin which are selected best PIMM and best resin in the previous sections, respectively. Each preform has the following specifications:

- Volume of each preform ($V_{preform}$) is 10.95 cm^3.
- Projected area of each preform ($A_{preform}$) is 8.815 cm^2.

The selected machine and resin specifications are shown in Table 7.1 and Table 7.5, respectively. Note that, the weight and projected area of runners, and sprue length are also neglected in this example. There are two equations coming from previous chapter to find optimum number of cavities. The lowest value will be the optimum value.

7.4.1. Determination of Optimum Number of Cavities With Respect to Shot Capacity of Machine

Determination of optimum number of cavity according to shot capacity of the selected machine can be found by:

$$Q_1 = \frac{S_{machine} * 0.8 * SG_{resin}}{SG_{PS} * \rho_{resin} * V_{part}} \tag{7.10}$$

By using Tables 7.1 and 7.5, Q_1 is obtained as 6.231 (i.e., **6**).

7.4.2. Determination of Optimum Number of Cavities With Respect to Clamping Tonnage of Machine

Determination of optimum number of cavity according to clamping tonnage of the selected machine can be found by:

$$Q_2 = \frac{CF_{machine}}{Q * A_{part} * CFE_{resin(max)} * VF_{resin}} \quad (7.11)$$

By using Tables 7.1 and 7.5, Q_2 is obtained as 9.88 (i.e., **9**).

7.4.3. The Final Selection

At this stage, the optimum number of cavities can be found by:

$$Q_{opt} = \min(Q_1, Q_2) \quad (7.12)$$

Therefore, it is equal to **6**. Note that, this value is obtained by using best PIMM and best thermoplastic resin. Therefore, a value greater than this value can not be reached by using another PIMM or thermoplastic resin.

7.5. CONCLUSION

In this example, sample databases for machines and materials are used. These sample databases are taken from [31,36]. Note that, in the complete databases, there are totally 27 thermoplastic resins and 623 PIMMs [31,36]. The name of companies and their number of machines in the machine database are:

1. Asian Plastics [37] (43)
2. Elite Precision [38] (81)
3. Krauss Maffei [39] (138)
4. Ning-bo Haitian [40] (48)
5. DGP Windsor [41] (236)
6. Tat-Ming [31] (31)
7. TMC [41] (42)

CHAPTER VIII

DISCUSSION and CONCLUSION

8.1. INTRODUCTION

Section 8.2 gives a discussion of the study. The need in the literature for this work and the most significant points of the developed system are also included in this section. Section 8.3 summarizes conclusions and contributions of this study. Section 8.4 covers the recommendations for future works.

8.2. DISCUSSION

Injection moulding process is the most traditional method of forming plastic materials into the desired shape. However, its complexity comes from the wide range of materials and machines. Using suitable material and machine in this process increases efficiency of the process and quality of the moulded part. There are several parameters affecting the efficiency and the quality. Insufficient or wrong knowledge will cause high costs and waste of time. Therefore, determination of these parameters requires a great experience on machine and plastic material science.

8.2.1. The Need for the Present Work

There are several works about injection moulding process in the literature. Many of the researchers studied on the design or determination of a single parameter of the injection moulding process. However, the relationships between all process parameters of the injection moulding were not considered or studied. Selection of the best machine and material during moulding process requires the construction of the relationships between all design parameters affecting the process. Therefore, the main aim of this study is to provide a design tool based on experiences in injection moulding industry.

There is a lack of Artificial Intelligence (AI) and Expert System (ES) applications on this subject in the literature. A few researchers works on this type of problem. As explained previously, the process is complex and there are many factors affecting this process. Determination of these factors and making the process more reliable require the establishment of the bridge among all factors and an Expert System (ES) can accomplish this goal.

8.2.2. The Structure of the Developed System

The developed system is called EXpert system for Plastic Injection Moulding Machines (EX-PIMM). This system is developed to obtain best machine(s) and material(s) for a given job. The system has three modules:

1. Module-1 (Selection of the best machine(s) from databases for a given material and defined part)

2. Module-2 (Selection of the best material(s) from databases for a given machine and defined part)

3. Module-3 (Determination of the optimum number of cavities for a given material and machine, and defined part)

The algorithms of first and second modules are similar. First module is used to obtain all feasible machines for a given part and material by using machine database file. Second module is used to obtain all feasible materials for a given part and machine. Third module is actually the combination of first and second modules.

It is used to determine the optimum number of cavities for a given part, machine and material.

Thermoplastic resins are selected as the domain of material database in this study. Machine database includes several Plastic Injection Moulding Machines (PIMMs) having different specifications. These databases are constructed by using Lotus 1-2-3 software. The current system can easily read/write necessary data from/to machine and material databases.

The GoldWorks Expert System Shell of the LISP language is used to create Knowledge Base (KB) files of the system. Each module has its own KB file. There are several IF-THEN rules and rule sets in their KB files. The contents of these KB files are different. During run-time of the system, each module use only its own KB file to find solutions. However, there is also a network relationship between these files. When a module is running, necessary data or rule can easily be read from other KB files, without loading them into the memory. In other words, only required KB files are used during run-time of the system. Therefore, this facility provides an effective and rapid generation of the solutions.

In the first and second modules, some tests are applied to "candidate" machines/materials contained in the databases, and at the end of these tests, some of them are eliminated due to insufficient capacity or capability for the defined job. Other machines/materials are said to be "feasible". After that, some other tests are applied to feasible machines to define their "awards" according to their specifications. A special award winning system is used in this system. Finally, all feasible machines/materials ascending in their award order are listed to the end-user. The best machine/material is selected by the end-user according to purpose. If the best machine and best material are used in the third module, then the most acceptable number of cavities for the given part can be reached.

There are some other KB files used by the system exclusively. These KB files have the functions required for reading/writing data from/to database files, displaying questions and results to the screen, and managing the KB files of three modules.

These KB files are loaded into the memory at the beginning of the program, and stay resident in the memory until the program is terminated.

8.3. CONCLUDING REMARKS

The most significant characteristics of the EX-PIMM can be summarized as:

- The current system has a modular structure. In other words, each module has its own KB file. However, during run-time, there is always a connection between these files.

- The current system is a frame-based system. Frames contain necessary slots and instances. All assigned data or value are hold in slots. In addition, instances work by using required slots contained in frames.

- This system is also a rule-based system. KB file of each module contains IF-THEN rules and/or rule sets. The current system reaches solutions by firing these rules and/or rule sets in the related KB files.

- Forward Chaining (FC) method is used in the first and second modules. In contrast, third module uses Goal-Directed Forward Chaining (GD-FC) method. In FC method, as in the case of conventional programs, all of the rules are fired in their created sequence. On the other hand, in GD-FC method, all of the rules are not used. Firstly, the problem is determined by searching the contents of KB file in reverse action. In other words, the sequence of the antecedent (IF part of a rule) and the consequent (THEN part of a rule) are changed to construct Backward Rules. After the problem is found, then system fires only Forward Rule or Rule Sets in forward action.

- Since, GD-FC method is used in the third module, computation time is reduced in this module. In addition, the efficiency and speed of this module is high compared to other modules due to the use of only small part of memory.

- A special award winning facility is created in the current system. There are some numerous tests to find all feasible (suitable) machines and materials. During each test, machines and materials win an award value according to the purpose of the test. At the end of all tests, total award value of each feasible machine/material are calculated and written to the machine/material database files for future use.

- The current system is independent from the knowledge. In other words, the domain of the machine and material databases does not affect the algorithm of the system. Therefore, when machine and material databases of the system are expanded in the future, the current system is also be able to run by using new expanded databases.

8.4. RECOMMENDATIONS FOR FUTURE WORKS

Advantages and some important characteristics of the current system are discussed in the previous section. However, some contributions should be made to the current system to increase efficieny and speed of the system. Recommendations and developments which could be adopted to current system can be listed as follows:

- The efficiency and speed of the current system might be increased by organizing KB files and writing additional functions for this purpose.

- The current system has 623 PIMMs and 27 thermoplastic resins in the databases. These databases may be enlarged for providing a wide range of choices to the end-user. Note that, this expansion in databases should not violate the efficiency and speed of the system.

- In the current databases, there are some lack of knowledge and misinformations in the specifications of machines and materials. By using equations in Chapter 5, this bottleneck could be eliminated by updating databases exclusively (manually). However, this should be done by the system so that end-user will not recognize this type of error during run-time of the system.

- Goal-Directed Forward Chaining (GD-FC) method should be used in all modules. This will cause a more efficient and rapid system. It will also create a less memory occupying system. In addition, the recent KB files will be easier to manage and organize, hence causing a decrease in computation time.

- AutoLISP programming is another growing usage of the LISP language. AutoLISP programming provides a relationship between LISP files and AutoCAD drawings. By using AutoLISP, some of the drawings or figures can be generated in AutoCAD environment by using functions written in LISP language. The integration of the current system to AutoLISP facility might be supplied. By this way, image of the defined part can be recognized by the LISP files, and this will provide a visual programming facility.

- Determination of injection moulding parameters is a complex task. Therefore, the terminology and nomenclature of the parameters used in the process require an additional experience. Beginner end-users having less knowledge about this terminology may need a "glossary" providing additional information about process parameters during run-time of the current system. This will construct a bridge between the less knowledge of end-user and the nomenclature of the process.

- Expert Systems (ESs) can explain their actions and justify their conslusions by the facilities of "explain" and "why" commands, respectively. However, these facilities could only be used from the inside of the Expert System Shell in GoldWorks. Therefore, a knowledge engineer or a knowledge base author is required to use "explain" and "why" commands in GoldWorks environment. These commands could be provided to the end-user without any need to a system analyst. This will make the current system more interactive.

- Finally, the current system may be integrated to other intelligent systems. The capability and efficiency of the current system may be developed by using other Artificial Intelligence (AI) techniques like Artificial Neural Networks (ANNs), Genetic Algorithms (GAs) and Fuzzy Logic (FL) in addition to Expert Systems

(ESs). Such systems are more reliable systems since one technique overcome the absence of other technique. This will provide some powerful contributions to the current system by eliminating the disadvantages of ESs.

LIST OF REFERENCES

1. Seow, L. W., and Lam, Y. C., December 1997, "Optimizing Flow in Plastic Injection Moulding", Journal of Materials Processing Technology, Vol. 72, No. 3, pp. 333-341.

2. Liang, J. Z., and Ness, J. N., February 1996, "Calculation of Cooling Time in Injection Moulding", Journal of Materials Processing Technology, Vol. 57, No. 1-2, pp. 62-64.

3. Turng, L. S., Chiang, H. H., and Stevenson, J. F., October 1995, "Optimizing Moulding at Low Injection Pressure", Plastics Engineering, Vol. 51, No. 10, pp. 33-36.

4. Ari, Gabriel, Zou, Quin, and Wilson, Jeff, 1995, "Systematic Approach for Solving an Injection Moulding Problem", Engineering Plastics, Vol. 8, No. 3, pp. 186-198.

5. Nee, A.Y.C., Fu, M.W., Fuh, J.Y.H., Lee, K.S., and Zhang, Y.F., 1997, "Determination of Optimal Parting Directions in Plastic Injection Mould Design", CIRP Annals - Manufacturing Technology, Vol. 46, No. 1, pp. 429-432.

6. Wang, Z., et al., 1996, "Optimum Ejector System Design for Plastic Injection Moulds", International Journal of Materials & Product Technology, Vol. 11, No. 5-6, pp. 371-382.

7. Li, C. S., and Shen Y. K., March-April 1995, "Optimum Design of Runner System Balancing in Injection Moulding", International Communications in Heat and Mass Transfer, Vol. 22, No. 2, pp. 179-188.

8. Hill, D., October 1996, "Further Studies of the Injection Moulding Process", Applied Mathematical Modeling, Vol. 20, No. 10, pp. 719-730.

9. Demirci, H. H., Coulter, John P., and Guçeri, S. I., February 1997, "Numerical and Experimental Investigation of Neural Network-Based Intelligent Control of Moulding Processes", Journal of Manufacturing Science and Engineering, Transactions of the ASME, Vol. 199, No. 1, pp. 88-94.

10. Kwong, C. K., Smith, G. F., and Lau, W. S., January 1997, "Application of Case Based Reasoning in Injection Moulding", Journal of Materials Processing Technology, Vol. 63, No. 1-3, pp. 463-467.

11. Shelesh-Nezhad, K., and Siores, E., January 1997, "Intelligent System for Plastic Injection Moulding Process Design", Journal of Materials Processing Technology, Vol. 63, No. 1-3, pp. 458-462.

12. Chin, Kwai-Sang, and Wong, T. N., August 1996, "Knowledge-Based Evaluation for the Conceptual Design Development of Injection Moulding Parts", Engineering Applications of Artificial Intelligence, Vol. 9, No. 4, pp. 359-376.

13. Steadman, Sally, and Pell, Kynric M., October 1995, "Expert Systems in Engineering Design: An Application for Injection Moulding of Plastic Parts", Journal of Intelligent Manufacturing, Vol. 6, No. 5, pp. 347-353.

14. Lim, J. T., Rho, H. M., and Cho, K. K., September 1994, "Knowledge-Based Process Planning System for Injection Mould", Computers & Industrial Engineering, Vol. 27, No. 1-4, pp. 95-98.

15. Zhongshuang, Yuan, et al., December 1993, "Integrated CAD/CAE/CAM System for Injection Moulding", Computing & Control Engineering Journal, Vol. 4, No. 6, pp. 277-280.

16. Choi, G. H., Lee, K. D., and Chang, N., 1994, "Optimization of Process Parameters of Injection Moulding with Neural Network Application in a Process Simulation Environment", Annals of the CIRP, Vol. 43, No. 1, pp. 449-452.

17. Lee, R-S, Chen, Y-M, Cheng, H.Y., and Kuo, M-D, 1998, "A Framework of a Concurrent Process Planning System for Mould Manufacturing", Computer Integrated Manufacturing Systems, Vol. 11, No. 3, pp. 171-190.

18. Kazmer, David, Rowland, John, and Sherbelis, Gal, March 1997, "Foundations of Intelligent Process Control for Injection Moulding", Journal of Injection Moulding Technology, Vol. 1, No. 1, pp. 44-56.

19. Önalır, Bülent, 1997, Computer Aided Simulation of Injection Moulding Process for Thermoplastic Materials, Msc. Thesis, Middle East Technical University (M.E.T.U.), Ankara.

20. Beck, Ronald D., 1970, Plastic Product Design, Van Nostrand Reinhold.

21. Frados, Joel, 1976, Plastics Engineering Handbook of the Society of the Plastic Industry (SPI) Inc., Fourth Edition, Van Nostrand Reinhold Company.

22. Rubin, Irvin I., 1972, Injection Moulding (Theory and Practice), Wiley-Interscience Publications.

23. Slagle, James R., 1971, Artificial Intelligence: The Heuristic Programming Approach, McGraw Hill.

24. Goldberg, E. D., 1989, Genetic Algorithms in Search Optimization and Machine Learning, Addison Wesley, USA.

25. Laudon, Kenneth C., and Laudon, Jane P., 1996, Management Information Systems (Organization and Technology), Prentice Hall.

26. Dereli, Türkay, May 1998, Development of a Process Planning System for Prismatic Parts, Ph. D. Thesis, The University of Gaziantep, Gaziantep.

27. Kaewert, J. W., and Frost, J. M., 1990, Developing Expert Systems for Manufacturing (A Case Study Approach), McGraw Hill.

28. --------, 1990, Knowledge Base Author's Manual, Knowledge-Based Expert System (KES PS), Software Architecture & Engineering Inc.

29. --------, 1989, User Guide, Goldworks II, Gold Hill Computers Inc.

30. --------, 1989, Reference Manual, Goldworks II, Gold Hill Computers Inc.

31. Tat-Ming Engineering Works Ltd., Hong Kong, http://www.catalog.com.hk/tatming/.

32. Niebel, B. W., Draper, A. B., and Wysk, R. A., 1989, Modern Manufacturing and Process Engineering, McGraw Hill.

33. --------, 1989, Lisp for Goldworks Users, Goldworks II, Gold Hill Computers Inc.

34. --------, 1989, Graphics Toolkit User Guide, Goldworks II, Gold Hill Computers Inc.

35. --------, 1989, External Interfaces, Goldworks II, Gold Hill Computers Inc.

36. Whelan, T., and Goff, J., 1990, Injection Moulding of Thermoplastics Materials, Volume I, Van Nostrand Reinhold.

37. Asian Plastic Machinery Co. Ltd., China, http://asianproducts.com/.

38. Elite Precision, Hong Kong, http://www.eliteprecision.com.hk/.

39. Krauss Maffei, Germany, http://www.krauss-maffei.de/.

40. Ning-Bo Haitian, China, http://www.xinxings.com/.

41. DGP Windsor India Limited, India, http://www.bicserve.com/htm/dgpwind/.

42. TMC Magnetics and Machinery Corp., Taiwan, http://www.tmcint.com/.

43. Milby, Robert V., 1973, Plastics Technology, McGraw-Hill Book Company.

44. Whelan, T., and Goff, J., 1990, Injection Moulding of Engineering Thermoplastics, Van Nostrand Reinhold.

45. Bernhardt, Ernest C., 1983, CAE: Computer Aided Engineering for Injection Moulding, Hanser Publishers.

46. Holmes-Walker, W. A., 1975, Polymer Conversion, Applied Science Publishers Ltd., London.

47. Bikales, Norbert M., ----, Moulding of Plastics (Encyclopedia Reprints), -----.

48. Dubois, J. Harry, and John, Frederick W., 1974, Plastics, Fifth Edition, -----.

49. Whelan, A., and Craft, J. L., ----, Developments in Injection Moulding (Improving Efficiency), ----.

50. Amstead, B. H., Ostwald, P. F., and Begeman, M. L., 1979, Manufacturing Processes, Seventh Edition, John Wiley & Sons.

51. Akbaba, Abdülhalik, 1973, Plastik İşletmecisinin El Kitabı, İktisadi İşbirliği ve Kalkınma Teşkilatı Yayınları.

52. --------, 1986, Design of Plastic Injection Moulds, Small Industry Development Organization (SIDO), The Design Department of Regional Development Centre.

53. Nilsson, Nills J., 1971, Problem-Solving Methods in Artificial Intelligence, McGraw Hill.

54. McLeod, Raymond Jr., 1993, Management Information Systems (A study of Computer-based Information Systems), Macmillan Publishing Company.

55. Kazmer, David, March 1997, "Best Practices in Injection Moulding", Journal of Injection Moulding Technology, Vol. 1, No. 1, pp. 10-17.

56. Chabot, Joseph F. Jr., and Malloy, Robert A., March 1997, "History of Thermoplastic Injection Moulding (Part I: The Birth of an Industry)", Journal of Injection Moulding Technology, Vol. 1, No. 1, pp. 1-9.

57. Dowler, Brian, and Coppari, Lawrence, June 1997, "Optimizing the Cooling of Small Injection Moulded Parts", Plastics Engineering, Vol. 53, No. 6, pp. 29-32.

58. Hill, Steve, April 1996, "Intelligent Process Control for Plastic Injection Moulding", Materials World, Vol. 4, No. 4, pp. 1.

59. Selden, R., December 1997, "Sandwich Injection Moulding Technology - Literature Survey", Journal of Injection Moulding Technology, Vol. 1, No. 4, pp. 189-203.

60. Bernhardt, Anne, and Kassa, Natalia, February 1996, "Benchmarking the Injection Moulding Process for Continuous Improvement", Plastics Engineering, Vol. 52, No. 2, pp. 31-33.

61. Deitz, Dan, "Optimizing Injection-Moulded Parts", Mechanical Engineering, Vol. 118, No. 10, pp. 89-90.

62. Hudson, J. A., June 1997, "Injection Moulding of Thermoplastic Elastomers : A Processing Guide", Journal of Injection Moulding Technology, Vol. 1, No. 2, pp. 117-122.

63. Yeung, V. W. S., and Lau, K. H., January 1997, "Injection Moulding, 'C-MOULD' CAE Package, Process Parameter Design and Quality Function Deployment: A Case Study of Intelligent Materials Processing", Journal of Materials Processing Technology, Vol. 63, No. 1-3, pp. 481-487.

64. Kwong, C. K., Smith, G. F., and Lau, W. S., October 1997, "Blackboard-Based Approach to Concurrent Process Design of Injection Moulding", Journal of Materials Processing Technology, Vol. 70, No. 1-3, pp. 258-263.

65. Hallum, Diane L., June 1997, "Fundamentals of Injection Moulding", Manufacturing Engineering, Vol. 118, No. 6, pp. 68-72.

66. Staniforth, Chris, "March 1997, "Injection Moulding", British Plastics and Rubber, pp. 22.

67. Rothe, J., November 1997, "Special Injection Moulding Methods", Kunststoffe Plast Europe, Vol. 87, No. 11, pp. 21-28.

68. Chin, K.-S., and Wong, T. N., 1996, "Developing a Knowledge-Based Injection Mould Cost Estimation System by Decision Tables", International Journal of Advanced Manufacturing Technology, Vol. 11, No. 5, pp. 353-365.

69. Thoma, H., November 1997, "Injection Moulding Machine Technology", Kunststoffe Plast Europe, Vol. 87, No. 11, pp. 17-21.

70. Miller, Thomas L., April 1996, "Injection Moulding", Medical Device and Diagnostic Industry, Vol. 18, No. 4, pp. 3.

71. Wang, Z., et al., 1996, "Optimum Ejector System Design for Plastic Injection Moulds", International Journal of Computer Applications in Technology, Vol. 9, No. 4, pp. 211-218.

72. Cho, K. K., Lim, J. T., and Oh, J. S., 1993, "Expert Process Design System Interfaced with CAD for Injection Mould Manufacture", Journal of Korean Institute of Industrial Engineers, Vol. 19, No. 2, pp. 119-132.

73. Cho, K. K., Lim, J. T., and Rho, H. M., 1992, "Development of Expert Process Planning System for Injection Mould", The Korean Society of Mechanical Engineers, Vol. 16, No. 12, pp. 2252-2260.