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The systemic analysis of injection moulding

Summary — Theoretical foundations [3, 4] and Rophol's formal definitions are used to carry out a systemic analysis of injection moulding. Technical systems are classified by function classes and major outputs (table 1) [3]. Primary shaping of products [9], *e.g.*, of thermoplastic melts, is described in terms of function classes (eqns. 1, 2). A general model of injection moulding is given (Figs. 1, 2) and systematic analysis of injection moulding, based on Rophol's formal definitions, is carried out (eqns. 3—13).
Key words: injection moulding, general model, systemic analysis, classification of technical systems.

The systemic analysis of polymer processing is a new field of polymer engineering [1]. This paper briefly discusses the theoretical prerequisites for an understanding of systemic analysis and analyses systematically the procedures of injection moulding. The intention is also to consider the primary shaping procedures: reactive and non-reactive injection moulding as a function of change in technical systems of things, which gives the opportunity for drawing conclusions. A short historical development of the problem has been described elsewhere [1, 2]

OBJECTIVES

The period of investigation is always followed by the period of systematisation.

Then, the period of systematisation would be followed by the period of investigation, etc.

(Vladimir Prelog, Nobel Price Winner in Chemistry)

The main purpose of the forthcoming discussion is to analyse the injection moulding of matter by the rules of systemic analysis, on the basis of certain theoretical considerations. This makes it possible to describe more than 105 various procedures of primary shaping which include common functions of preparation of matter for injection, injection itself, primary shaping and structuring.

THEORETICAL FOUNDATION

The systemic analysis to be applied in this study on injection moulding procedures, is based on four fundamental ideas, *viz.*, (*i*) J. Beckmann's concept of general technology [3], (*ii*) the cybernetic postulate of flow of matter, energy and information [3,4], (*iii*) the systemic theory of technology [3], and (*iv*) shear viscosity as the summing up parameter of matter [5].

KEY CONCEPTS

The starting idea for the systemic analysis of injection moulding comes from J. Beckmann's (1806) paper entitled *"Entwurf der allgemeinen Technologie"* (*cf.* [3]). The key sentence is: *The totality of the procedures that are found in a variety of trades should be taxonomically classified in terms of their identical or similar purposes, with each group of procedures involving a similar working tool, whereas the kind of material that is subjected to working is of secondary importance.*

According to the postulate of cybernetics, all the phenomena in this world can be represented as matter, energy or information [4]. This postulate may be applied in the description of system concepts, of which there are three: hierarchical, functional and structural [3]. The use of systemic concepts in the manufacture of plastics products for the injection-blow moulding system has been described by Čatić and Razi [2]. These concepts may be defined in formal mathematical terms, and the definitions are based on the set theory [3]. The paper shows these concepts in the description of a polymer injection moulding system [2].

TECHNICAL SYSTEMS OF THINGS

Polymer processing systems like an injection moulding system should be viewed as technical systems of things [2]. These systems are man-made and include intentionally used products of man's intentions and work [3].

Polymer processing systems may be ranked so that higher-rank systems are formed by the combination of lower-rank systems of things. Thus, for instance, the injection moulding machine, the mould and the heat exchange device make up the injection moulding system. At the next higher level, the injection moulding system and the blow-moulding system (blow machine, blow mould, and heat exchange device) form a single manufacturing system known as the injection-blow moulding system.

As a further step, technical systems may be classified by function classes and principal outputs (Table 1) [3].

Table 1. Classification of technical systems of things [3]

	Change (production technology)	Transport (transport technology)	Storage (storage technology)
Matter (material technology)	processing technology, manufacturing technology	conveying technology, traffic technology, civil technology	stockage technology, building construction
Energy (energy technology)	energy conversion technology	energy transmission technology	energy storage technology
Information (information technology)	data processing technology, measurement and control technology	information technology transfer	information storage technology

In Table 1, the row represents the postulate of cybernetics concerning the flow of matter, energy and information. The column shows the function classes: change, transport and storage. In polymer processing the function class of special interest is the change, which may be either transformation or change-over. A combination of the principal output matter and the function class of change is described as the production technology. It consists of a system of things which includes process technology and manufacturing technology. The process technology system of things embraces matter characterised by defined properties. The output of manufacturing systems of things are real products with defined shape and part properties [1, 3].

REACTIVE PRIMARY SHAPING AS A FUNCTION OF CHANGE

In technology, a distinction can be made between technological products (*e.g.*, machine systems) and technological procedures or processes [3]. Both these categories are indispensable to converting natural non-processed matter (*e.g.*, petroleum) into an artificial, finished product (*e.g.*, a plastic automobile fender), and their common denominator is the production of artefacts [6]. One of the main characteristics of the production of polymeric parts is the fact that it is possible in some cases, to produce simultaneously a material of required physical and chemical properties (process technology) and a product having the required geometrical shape and quality (manufacturing technology) (Fig. 1) [7, 8]. All of this takes place during the procedures which fall under the category of reactive primary shaping. The product can be compact or foamed. In general, the polymer processing systems like systems for reactive or non-reactive injection moulding, should be viewed as technical systems of things [2].

FUNCTION CLASS OF CHANGE IN THE MAKING OF PRODUCTS

The function class of change can be considered at the macrolevel and the microlevel. The geometrical shape

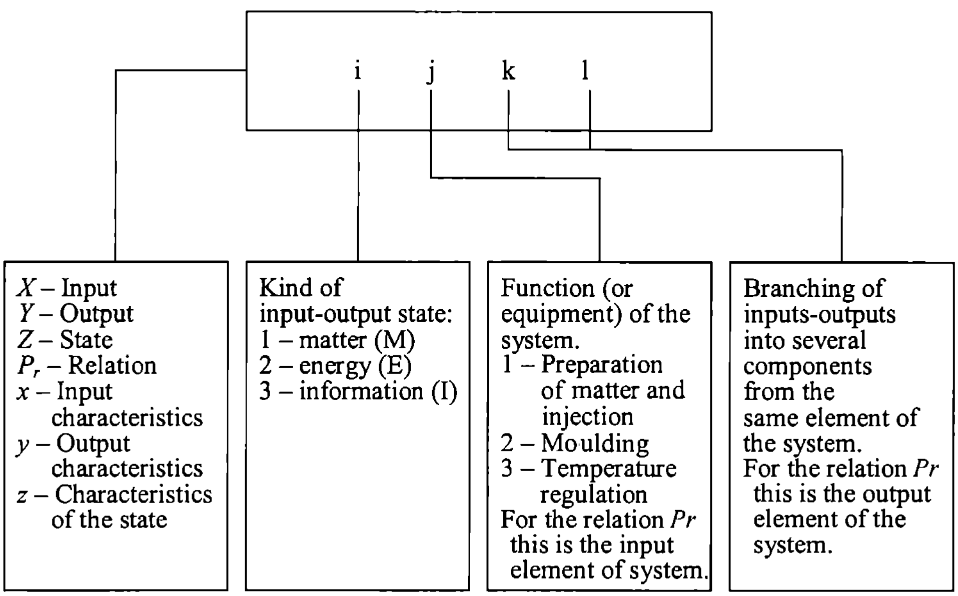

Fig. 1. Representation of the injection moulding system [1]

of products depends primarily upon the geometrical shape of the cavity and can be regarded as a result of the macrophysical process (macrolevel). Creation of the structure of parts is the result of chemical and/or physical processes and, according to Bense [3], can be regarded as a result of microphysical processes (microlevel). From the classification of technical systems of things follows that the function class change (F_C) can be divided into two sub-functions: the manufacturing function (F_{CM}) and the processing function (F_{CP}) [3]. The making of a matter endowed with required properties as a result of the processing function can be understood as the structuring function.

In all the procedures of production of goods, such as polymeric materials, the manufacturing functions exist without exception [3]. According to a German Standard DIN 8580, the manufacturing functions can be divided into two main groups [9]. The first is to establish a connection between the particles, making a primary geometrical shape. This is the primary shaping function ($F_{CM,\, ps}$). The second group is reshaping, which includes the processes of maintaining, decreasing and increasing the connection between the particles ($F_{CM,\, rs}$)

The process or structuring function F_{CP} is always connected with the manufacturing function, but in various ways and at various levels. The structural state achieved can be regarded as a result of conscious desire (*e.g.* chemical reactions of polymerisation and/or cross-linking) or the consequence of the influence of, *e.g.*, the shape of parts (*e.g.*, heterogeneous cooling of different layers of mouldings resulting in internal stresses). The structuring can be divided into groups: primary structuring (creating the primary structure) and restructuring (changing of primary structure) [7, 8, 10]. The function of primary structuring can be designated as $F_{CP,\, ps}$ and that of restructuring as $F_{CP,\, rs}$. The primary structuring of polymeric materials at the molecular level is the result of chemical processes and structuring at supramolecular and higher levels of physical processes.

PRIMARY SHAPING OF PRODUCTS

According to DIN 8580 [9], primary shaping can be defined as the making of solid bodies from shapeless matter, wherefore the connection between the particles is achieved and the structure formed (primary structuring) [10]. According to Käufer [11], the primary shaping of polymeric products can include: primary shaping involving chemical making of material, primary shaping involving physical making of material from solutions or dispersions, and primary shaping of melts [12]. Generally, the primary shaping of thermoplastic melts can be regarded as a kind of physical primary shaping of matter with the change of state (*e.g.* solid into liquid state). In terms of types of function classes, reactive (chemical) and non-reactive (physical) primary shaping can be distinguished.

In the case of reactive primary shaping of compact mouldings, the function of change must contain the following partial functions:

$$F_C = F_{CM,\, ps} +^{*)} F_{CP,\, psm} + F_{CP,\, pss} + F_{CP,\, rsm} = F_{CPSR} \quad (1)$$

The following partial functions describe non-reactive primary shaping of compact mouldings:

$$F_C = F_{CM,\, ps} + F_{CP,\, pss} + F_{CP,\, rsm} = F_{CPSN} \quad (2)$$

By the equations (1) and (2), the function of establishing a connection between the particles ($F_{CM,\, ps}$) and the primary structuring is always present at the supramolecular and higher levels ($F_{CP,\, pss}$). This type of primary structuring includes the orientations, internal stresses and, on processing of semicrystalline thermoplastics, the degree of crystallinity. Also, the primary structure can be changed at the molecular level ($F_{CP,\, rsm}$) by means of desirable or undesirable chemical reactions. During reactive primary shaping the primary structure at the molecular level can be achieved by chemical reactions of polymerisation and/or cross-linking ($F_{CP,\, psm}$). This is one of the particularities of the production of polymeric parts.

The cyclic procedures of primary shaping are called moulding. In these procedures, the function of primary shaping takes place in the proper means of action, mould. If the function of primary structuring on molecular level must be fulfilled during the moulding, the mould must be regarded and serves as a batch reactor.

INJECTION MOULDING OF MATTER

Procedures investigated

The groups of procedures which can be described in the sense of Beckmann's requirement of the identity or similarity of the type of procedure such as injection moulding, and for what kind of a matter these procedures are suitable, are given below [12].

High pressure procedures:
— injection moulding of thermoplastic melts,
— co-injection (sandwich) injection moulding,
— lost-core injection moulding,
— injection moulding with double injection,
— encapsulation of prefabricated parts made from different materials by injection moulding,
— special procedures of injection moulding of thermoplastics,
— injection moulding with decoration in mould,
— injection moulding of thermosets,
— injection moulding of rubber compounds,
— special procedures of injection moulding of other matters and materials (ceramics, metal granulate, powder, melt).

*) The signs » + « in equations (1) and (2) indicate only that these functions exist, and do not refer to the nature of relations between the functions.

Low pressure procedures:
— fluid injection moulding,
— gas-assisted injection moulding,
— liquid-assisted injection moulding,
— other low pressure procedures,
— reaction injection moulding procedures,
— multicomponent reaction injection moulding (MC-RIM),
— other reaction injection moulding procedures.

General model of injection moulding of matter

The procedures of injection moulding of polymers have been examined in the light of Ropohl's formal definition [2].

The generalisation of the model embracing the system for injection moulding of low viscosity liquids [13] and the system for injection moulding of polymer melts [2] has enabled a general model of injection moulding of matter to be developed (Fig. 1) [1, 14].

Figure 2 shows the necessary functions involved in injection moulding: preparation of matter, injection, primary shaping and structuring (moulding), and reaching the prescribed temperature. The context in which the injection moulding system functions for the primary shaping and structuring of matter, represents the environment which determines its conditions of operation: pressure, temperature, and humidity.

Owing to its generalised nature, the above model of the system of injection moulding for primary shaping and structuring of matter is informationally sparse. That is why a more precise description of each procedure requires an appropriate separate model to be used. In preparing the matter for injection moulding, a change of state may occur (*e.g.*, injection moulding of thermoplastics) or compounding of different substances may take place (*e.g.*, RIM). Injection may be high-pressure (*e.g.*, injection moulding of cross-linkable rubber) or low-pressure (*e.g.*, pressure gelling of epoxy resins). Matter may be injected into the cavity in a high-viscosity state (*e.g.*, injection moulding of thermoplastics), in the low-viscous liquid state (*e.g.*, RIM), or in the very high viscosity (solid) state (*e.g.*, low-pressure casting of sand mixture with phenolics as binders).

After having been injected into the cavity of the mould, the matter and/or the material assumes its final form on cooling (*e.g.*, injection moulding of thermoplastics) and by some type of reaction. At the same time, structuring takes place on the molecular or on supramolecular level. The preparation and injection units, as well as the mould, must have the prescribed temperature which is achieved by temperature control.

Not all the inputs and outputs of these relations occur in each injection moulding system. Thus, for instance, heat supply from the environment to the mould occurs only during the injection moulding of thermoplastics when the mould surface temperature is below that of the environment. In all other cases the environment carries the heat away from the mould. For instance, volatilisation occurs during the injection moulding of thermosets. This is the reaction that sets in during the processing of cross-linkable matter with polycondensation.

The information input into the mould and the feedback information are of particular importance in injection moulding.

Systemic analysis of injection moulding

The systemic analysis of injection moulding of matter has been partially described in [2]. This analysis is based on Ropohl's formal definitions, and is now completely available only in [15].

There are 40 Ropohl's formal definitions [3] (indicated in parentheses) that have been used for the description of injection moulding of matter.

The system of things S_S consists of α_S attributes A_i, φ_S sets of functions F_j which could be realised on the basis of natural laws, σ_S sets of artificial, actual sub-systems S'_S and sets of relations P_m (so-called structures). Attributes, functions, sub-systems and relations represent all the aspects of a system of things (defs. 1, 2, 25).

Attributes A_i of injection moulding system of matter α_S include material, M_i, energetical, E_i and informatical, I_i attributes, co-ordinates of space R and time flow V of input X, output Y and state Z, as well as connections (relations) between the sub-systems (defs. 3, 25).

Definitions 4—6 and 22—24 describe the types of functions. From the description of equations (1) and (2), and the function (def. 28a) follows that during the injection moulding of matter, the functions: establishing a connection between the particles ($F_{CM,\,ps}$), primary structuring at the supramolecular and higher levels ($F_{CP,\,pss}$) and restructuring at the molecular level ($F_{CP,\,rsm}$), or in total, function F_{CPSN} always exists.

In the case when the process of injection moulding is accompanied by reactions, the process function of primary structuring at molecular level $F_{CP,\,psm}$ is present (def. 28b). This means that, strictly speaking, the injection moulding of thermosets, prepolymers, and rubber compounds is also a reaction injection moulding. When the process function $F_{CP,\,psm}$ is present, during the primary shaping, the mould always acts as a batch reactor.

The transport function F_T (def. 29) is a feature of mould filling with the matter at the necessary shear viscosity. The function of storage F_S also exists, and the matter as well as energy can be stored (def. 30). In the injection moulding process the function change of state F_{CS} (def. 31) is permanently present. According to def. 31 and supported by the analysis of matrix of injection moulding process the injection moulding of matter is a nonstationary process. The function of maintaining of state exists only when the preparation unit is separated from the injection unit, *e.g.*, compounding of substances is not connected with the injection function.

A nonstationary system of things, as the injection moulding system is, with the input as information com-

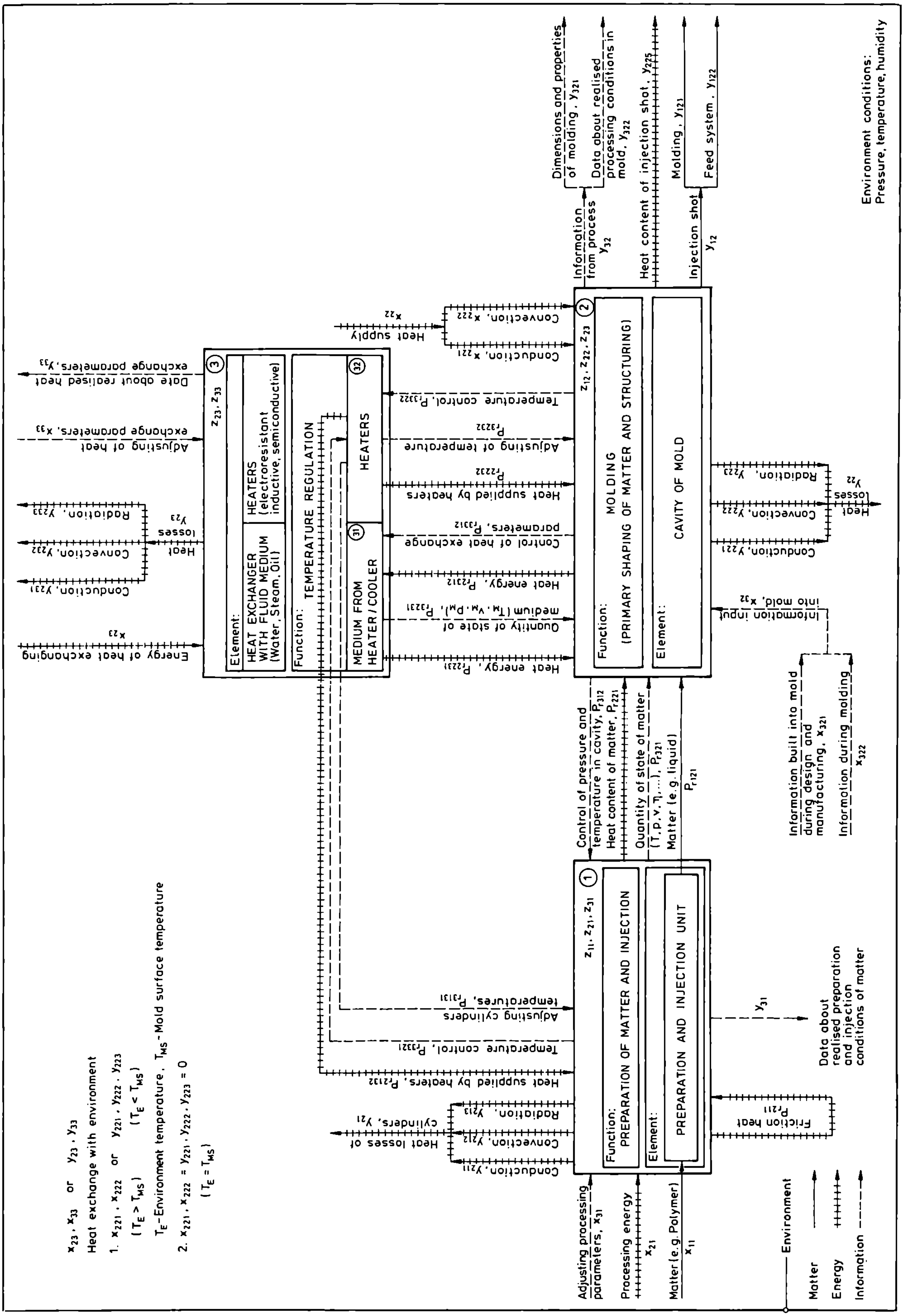

Fig. 2. Injection moulding system for primary shaping of matter [1]

mand I_C (A_{xi} = I_C) is according to def. 33 governing. In contrast to the injection moulding process, which is always nonstationary, the flow of information during this process can be achieved to be a stationary [1, 16].

By using definitions 7 and 34 one can pass from the functional to the hierarchical concept of the system. In the case when the functions of preparation of matter and injection are unified, the injection moulding system, which may be at the same time regarded as the true system (defs. 14 and 38) consists of three sub-systems. These sub-systems, according to def. 25 can be at the same time regarded as the systems with the same attributes, functions and categories as the injection moulding system. According to definitions 11—33 and 37 of the injection moulding system, the injection moulding system, is for instance, the super-system, and the injection moulding machine or mould is a sub-system.

The structure of the system involves material, energy and information connections and spatial and temporal relations. Each system is surrounded by the technical environment of a thing.

According to (def. 15) the system of target exists only when the given system contains the set of sub-systems (σ) and the set of relations (π). In the injection moulding exist the following sub-systems of functions: preparation of matter (C_{11}), injection (C_{12}) ($C_{11} + C_{12} = C_1$), moulding (C_2) and reaching of prescribed temperatures (C_3). Reaching the prescribed temperatures is intended to occur in the preparation unit (C_{311}), injection unit (C_{312}) and mould (C_{32}) (C_{32} = C_{321} — starting temperature field, C_{322} — quasi-stationary temperature field). The starting temperature field in the mould can be described as:

$$\sigma_s = \{C_1, C_2, C_3\} \quad (3)$$

Simultaneously, there exist the sets of relations: relation of indifference, relation of instrumentation and relation of preference.

$$\pi_s = \{P_{Idf,m}\} \cup \{P_{Ism,m}\} \cup \{P_{Pfr,m}\} \quad (4)$$

From the (def. 16) follows that the relation of indifference exists between the targets

$$P_{Idf,m}(C_{11}, C_{321}) \Leftrightarrow \exists C_{11} \wedge \nexists C_{321} \quad (5)$$

The meaning of equation (5) is that it is not important whether the prescribed temperature of preparation unit or the necessary temperature field in the mould is reached first.

Five instrumental relations may be identified (def. 18). First, it is necessary to reach the prescribed temperature of the preparation unit and then the one of the injection unit:

$$P_{Ism1}(C_{311}, C_{11}) \Leftrightarrow \exists C_{311} \rightarrow \exists C_{11} \quad (6)$$

$$P_{Ism2}(C_{312}, C_{11}) \Leftrightarrow \exists C_{312} \rightarrow \exists C_{11} \quad (7)$$

Strictly, the quasi-stationary temperature field in a mould can be reached only after several cycles, because the injected matter transfers into a mould a certain quantity of heat. Therefore, this shall be considered a starting mould temperature field the one, represented by the minimum temperature on the cavity surface during the cycle, enabling the moulding to be produced with a lower, but acceptable quality. In this case the instrumental relation can be written as follows:

$$P_{Ism3}(C_{321}, C_{12}) \Leftrightarrow \exists C_{321} \rightarrow \exists C_{12} \quad (8)$$

The function of moulding cannot be fulfilled before the function of injection is fulfilled:

$$P_{Ism4}(C_{12}, C_2) \Leftrightarrow \exists C_{12} \rightarrow \nexists C_2 \quad (9)$$

After moulding has been completed, the stationary temperature field in a mould can be reached:

$$P_{Ism5}(C_2, C_{322}) \Leftrightarrow \exists C_2 \rightarrow \exists C_{322} \quad (10)$$

After the first injection of matter into the mould, some time is necessary to reach a quasi-stationary temperature field in the mould, as follows from the relation of preference (def. 19). For moulding it is more important to have the conditions for injection fulfilled, rather than the quasi-stationary temperature field in mould:

$$P_{Pfr}(C_{12}, C_{322}) \Leftrightarrow \exists C_{12} \rightarrow \nexists C_{322} \quad (11)$$

Based upon the relations following defs. 16, 18, 19, the set of relations (def. 15) can be written in the form:

$$\pi_s = \{P_{Idf1}\} \cup \{P_{Ism1}, \ldots, P_{Ism5}\} \cup \{P_{Pfr1}\} \quad (12)$$

According to def. 20 the chain of target L_T for injection moulding system may be defined as:

$$L_T = \{P_{Ism1}, \ldots, P_{Ism5}\} \quad (13)$$

General definition of injection moulding

By defining the chain targets, the order of individual function development is fixed. The definition of the chain of targets, as well as the definition of main partial functions of the mould, enables the general definition of injection moulding and the definition of information flow to be determined [1, 15].

In formulating a general definition of injection moulding, it is necessary to find a parameter that reduces all the observed matter to a common denominator. According to Lenk, this parameter is shear viscosity [5]. Lenk believes that the main state of all matter is liquid, and that the solid and gaseous states are only special forms of the liquid state. Adoption of this view, based among other things on the fuzzy set theory (fuzzy variables), makes the adoption of a general definition of injection moulding of matter possible. The definition starts from the function of procedures and describes the flow of matter and energy as a process.

Injection moulding (die casting) of matter is an over-pressure cyclic mode of procedure of primary shaping. Matter with the necessary shear viscosity is injected into a cavity with the prescribed temperature. The product, a moulding, with a defined shape and properties is obtained by gelation and/or cooling, some kind of reactions, such as polymerisation and/or crosslinking or some other mode, and it can be subsequently demoulded.

The definition of information flow is: Close-loop control of injection moulding process can be achieved by interaction of single functions. The change in the information flow of one function (*e.g.*, injection) must be corrected by interaction of other functions (this can be realised *e.g.*, with the aid of one superordinate regulator).

It must be pointed out that both these definitions are informatically very sparse owing to the very high level of model's abstraction. For this reason, for each single procedure an appropriate definition must be worked out. As examples, we give two definitions, first, for injection moulding process for thermoplastic melts, and second, for reaction injection moulding of integral polyurethane foamed parts [15].

From the point of view of flow of matter and energy (process definition), the injection moulding of thermoplastic melts is a high-pressure cyclic mode of procedure of (non reactive) primary shaping. A thermoplastic melt with the necessary shear viscosity is injected into a cavity with the prescribed temperature. The product, a moulding, with the defined shape and properties, is obtained by gelation and/or cooling, and it can subsequently be demoulded.

The process definition of reaction injection moulding of integral polyurethane foamed parts may be written as a low-pressure cyclic mode of procedure of reactive primary shaping. The compound of matters with the necessary shear viscosity is injected into a cavity with the prescribed temperature. The product, a moulding, with the defined shape and properties is obtained by polyaddition and cross-linking, accompanied by foaming, and it can subsequently be demoulded.

CONCLUSIONS

The particular value of systemic approach is that it points at the universality of occurrence and generates questions which otherwise would have never been asked. The systemic approach allows a range of very meaningful conceptions and theories to be created and included like cybernetics, information technology, ecology, *etc.* In resolving single, actual problems, the systemic approach offers a general conception base, the methodology of design and improvement of systems, scientific method, *etc.* [3].

The main purpose of the present discussion is to reach a better understanding of the processes that take place in different systems, to make the necessary generalisations, and to formulate general rules.

To realise this requirement, on the basis of certain theoretical consideration, injection moulding of matter has been systematically analysed.

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