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ON THE DEFINITION OF PARAMETRIC DESIGN PROBLEMS FOR COMPUTATIONAL SYNTHESIS

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ABSTRACT
This paper presents *parametric design definition* as a common framework for creating representations of parametric design problems that can be used for the development of solution approaches for computational synthesis activities. Design definition is presented as a three folded activity that accounts the process of exploring, structuring and creating models of parametric design problems. In this work, the accent is set on the design exploration phase. Design exploration aims at formalizing the parameters and relations required for describing a parametric design problem. First, the information content that should result from such a process is investigated. Then, a Function Behavior Structure based Design Exploration (FDE), is formulated for assessing the required information. The methodology uses Function-Behavior-Structure modeling in combination with an analysis based information flow classification to explore the set of parameters required for describing a design problem. The methodology is demonstrated for the design of cooling system for injection molding. Further work, required for the development of the framework, is discussed.

Keywords: Design definition, parametric design, computational synthesis, methodology

1 INTRODUCTION
Engineering design synthesis can be thought of as attempting to create form to fulfill desired behavior [1]. It involves both qualitative and quantitative aspects. The synthesis process can be divided into two phases, namely, conceptual synthesis and parametric synthesis [2]. Conceptual synthesis regards the process of generating conceptual solutions, usually represented by elements within a given topology [2]. Parametric synthesis seeks the specification of the properties of the elements present in the encountered topology [2]. Synthesis research activity can also be differentiated into paper based methods (i.e. axiomatic design [3]) and computational methods (i.e. agent based synthesis [4]). Computational synthesis has appeared as an attempt to assist the engineering design process by means of computational production systems.
Within the field of computational synthesis, Artificial Intelligence (AI) and Operations Research (OR) computation techniques have been broadly used in developing solutions approaches to design synthesis problems [5]. Frameworks as Function-Behavior-Structure (FBS) have been successful in assisting the representation of conceptual designs, serving as bridge between AI/OR based methods and the synthesis process to be automated, as can be seen in [5], [6], [7] and [8]. To mention an example, Startling et al. [6] used FBS to develop a parallel grammar for design synthesis of mechanic clocks. An FBS design model of the clock was produced to map the possible Functions to embodiment Structures. A Function grammar (defining the connectivity between Functions) and a Structure grammar (based in the topologic relations of the clock) are used simultaneously to generate a solution.
The basis of Function-Behavior-Structure is to carry out the transition from function to structure via the synthesis of physical behavior. In this fashion, behavior allows characterizing the implementation of a function [9]. The generic nature of FBS resides in its capability to describe design objects at different representation levels together with the relations that exist among them.
In the context of the FBS scheme, a design problem can be said to be one in which a design object has not been fully described in its different representation levels. Solutions are then found by completing

these descriptions, which represent coherently a design object, by performing different synthesis activities, like:

1. Generate sub functions that specify the scope of the general functional statements of the design.
2. Reason about the behaviors that allow the existence of the given functions.
3. Generate concept structures that allow the existence of the expected behaviors.
4. Instantiate the conceptual design object to meet the characteristics of the expected behavior.

For the functional and conceptual design phases (1, 2, 3) several paper-based methodologies have been developed for the synthesis phase (see [10], [11] and [12]). Hari et al [10] developed ICDM (Integrated, customer driven, Conceptual Design Method) as support for the conceptual design phase of new products. This paper-based methodology consists out of ten steps that guide a conceptual design trajectory from customer requirements down to launching the project for the full scale development [10]. According to [10], prescriptive methods (consisting of stepwise procedures, and mainly based on German systematic approach), became the most widespread. Industry adopted some of these techniques to shape different Product Creation Processes [13]. Computational synthesis research also resulted in different methods for the concept design phase, as in [4], [14] and [15]. For Example, Zhang et al [6] developed a Knowledge-Based System for Conceptual Synthesis (KBSCS) that infers physical behavior from a desired function. A model representing causal relations between the function and behaviors was created and used to select an arrangement of structure elements to develop the systems configuration, whose end result is a concept design.

For the parametric design process (4), many models that describe the relevant relations and variables representing a concept design object, are available in different domains of engineering design practice (e.g.[2], [16]). For example, the parametric design of springs is specified in several mechanical engineering books, where analytic models can be used by designers to start an instantiation process. These models have mainly risen from analysis techniques relating physics principles with structure variables. In the case of a spring design, solid mechanics theory defines the set of variables that need to be taken into account for the instantiation process.

However, no frameworks have been found to aid the process of developing parametric models of the concept design object emerging from the synthesis process itself. Of course, analysis techniques are of paramount importance when developing such models, as long as it is motivated by requirements originated in the synthesis process. In modern engineering design practice, where multi functional and multi-domain design approaches result in more complex artifacts, such methodologies can aid designers in the process of generating solution approaches. For computational synthesis, it aids the translation of parametric design problems into methods for computational synthesis (AI and OR), as well as its implementation into computer programs. In addition, it can support the translation of industrial design problems into computational synthesis tools, one of the major challenges facing computational synthesis at present [17]. Therefore, this paper discusses an attempt to develop a methodology for formalizing models of the design artifact that are in agreement with its functional and behavioral specifications, and has been regarded as *Definition of Parametric Design Problems*. This is the first step towards the development of a common framework for the implementation of computer synthesis tools for parametric design problems. It is expected that counting with robust methodologies for the definition of parametric design problems for computational synthesis will allow:

- Identifying whether a given design problem is parametric.
- Identifying the knowledge that is required for describing the design problem parametrically.
- Organizing and structure the information in such a way that decision making problems can be identified and categorized.
- Developing a design problem model on which strategies can be formulated for its translation into computational synthesis tools.

The relevance of computational synthesis tools for parametric design problems is based on the fact that many designs in the industry are different instances of proven concepts. As consequence, several design problems reduce to that of starting a new instantiation process. Examples can be found in mechanical engineering design book, where theory about design of springs, cams, transmission belts, among others, is documented and intensively used by engineers in more complex design processes. Manufacturing industry also presents cases of parametric design problems. Examples are design of injection molds and extrusion dies, each being composed of several integrated parametric design problems. The development of computational synthesis tools for such design problems aim at assisting the designer as CAD tools for the parametric design phases.

The paper is structured in 7 sections. Section 2 builds on the concepts and scopes of parametric design definition. Design definition is presented as a three folded activity that accounts the processes of exploring, structuring and creating models of parametric design problems. In this paper the focus is given to the design exploration phase. Section 3 elaborates in the information content that is searched in the design exploration process. Section 4 presents the design of cooling systems for injection molding as selected case study for the demonstration of the methodologies originating from the present research. In section 5 a methodology for performing design exploration is presented and demonstrated in the case study. Future work will focus on design structuring and model development. Section 6 presents a global view of these aspects, while section 7 presents some conclusions.

2 DEFINITION OF PARAMETRIC DESIGNS PROBLEMS

According to the Oxford English dictionary, the word *definition* can be understood as: (1) a statement of the exact meaning of a word or the nature or scope of something, (2) the action or process of defining, and (3) the degree of distinctness in outline of an object or image. In Wikipedia it is expressed as: (1) determination of the limits, (2) a statement expressing the essential nature of something, and (3) the action or power of describing, explaining, or making definite and clear**.**

In the context of the FBS framework, parametric design problems can be said to be those where a complete functional and behavioral description exists together with descriptions about the structures and topologic relations that define the conceptual design artifact. Gero et al [15] have defined this type of design problems as routine design, *'in which the design space of the functions, expected behaviors and structure variables is known and the problem is one of instantiating values for structure variables'*.

From the before said, *definition of parametric design problems* can be regarded as the process of describing, explaining, delimiting, and making definite models of parametric design problems. It is done with the aim of counting with clear statements of a design problem from where solution approaches for computational synthesis can be derived. In the context of this work, parametric definition is the process through which a parametric design problem is formally identified and described by means of structures[1] that aid designers in the development of computational synthesis tools. The description of the problem should explicitly reflect the structure[1] and relations that originate the design problem. Therefore, we propose the definition phase as a three-folded activity that accounts the processes of: (a) exploring the parameters required for the representation of a given conceptual design, (b) structuring[1] it so that the problem can be divided in smaller chunks and (c) developing a meta-model that captures the structure, components, parameters and relations on which the instantiation process can take place to result in full descriptions of the design object. Figure 1 illustrates the design definition processes.

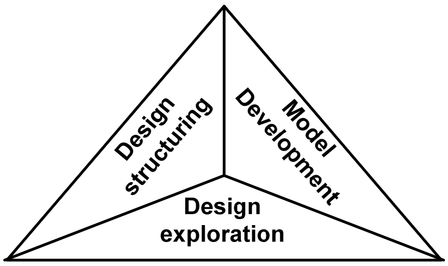


Figure 1: Design definition of parametric design problems

From here it follows that the main questions motivating this research work are:

- Design exploration: What for information content is required for the definition of such parametric model? How can this information be assessed for a given design problem?
- Design structuring: What for structures[1] can be identified in parametric design problems? How can a given parametric problem be structured[1]?
- Model development: How can information and structure[1] be represented in a parametric model of the design problem? How can this be implemented in a given parametric design problem?

For each of the process, a descriptive approach is used for answering the first questions, while prescriptive methods try to answer the seconds.

[1] Structure is temporally regarded as the process of organizing.

3 DESIGN EXPLORATION: INFORMATION CONTENTS

The purpose of designing is to transform function into a design description so that the design object being described is capable of producing those functions [15]. Design descriptions allow representing objects elements and their relationships. This is usually done by means of graphics, mathematics and texts [15]. This implies that design involves the process of exploring the entities as well as the relations required for representing a design artifact. FBS modeling and an analysis based information flow classification serve therefore as theoretical background for determining the set of entities and relations that: (1) define the topology and dimensions of the design, (2) describe artifact's surrounding environment and (3) allow assessing the behavior of the artifact relative to a given function.

3.1 Function-Behavior-Structure Modeling

Function-Behavior-Structure (FBS) modeling allows the representation of a design by distinguishing three levels of object representation: Function, Behavior and Structure [18]. Function is related to the perception designers have on an object structure. Behavior is related to the sequential change of states the object goes through for delivering the required function. Structure is related to entities, relations among entities and the attributes of entities for physical representation of the design object. By using these three design object representation levels, FBS modeling allows linking a design Function to an eventual form or Structure that fulfils the required Function. To do so, an intended Function is related to Behavior that allows the Function to exist by a human specified mapping. Behavior is related to the response of a Structure for producing the required function by Fundamental Principles, also regarded as laws of physics [18].

Many studies on FBS modeling can be found among the engineering design community [9], [15], [19]. Zhang et al. [9] presented a unified model referred to as Function-Behavior-Principle-State-Structure (FBPSS). The model is based on the analysis and generalization of different research work found in the literature, and it served as reference for relating the different views. The reference model uses the following concept definitions for a proper design object representation:

- Structure: Is a set of entities and relations among entities in a meaningful way. Entities are perceived in the form of their attributes when the system is in operation.
- State: Are quantities (numerical or categorical) of either physical or chemical domains. These represent the attribute of a Structure entity. States change with respect to time, implying the dynamics of the system.
- Principle: Is the fundamental law that allows the development of a quantitative relation for the States variables. It governs Behavior as the relationships among a set of State variables.
- Behavior: Represents the response of the Structure when it receives stimuli. Since the Structure is represented by its States, the stimuli and the responses are further represented by the State variables.
- Function: It is about the context sensitive usefulness of a system (structure) for its existence.

Figure 2 shows how these definitions are related. The relationship between State and Structure is a one-to-many relation. The Behavior is produced as the combination of State sets underlined by a given set of Principles to the Structure. Behavior and Function have a many-to-many relation, which depends on the context and usefulness of the Structure.

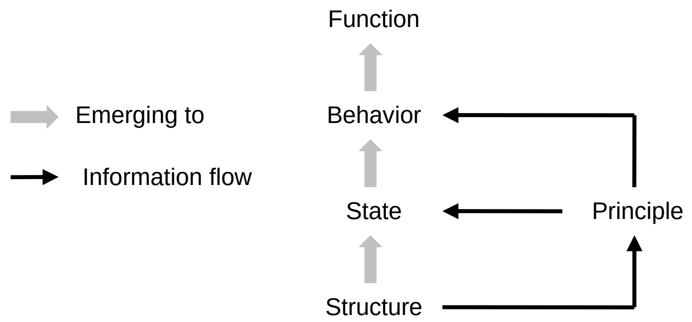


Figure 2: Relation between Function-Behavior-Principle-State-Structure [9]

Design objects Structure can be described by three properties: vocabulary of elements, description of the elements and the configuration of the elements [13], as seen in Figure 3. The Figure illustrates how a design structure is composed by different elements in a given configuration with a given description. The goal of design exploration is, in this terms, to formalize these three properties such that consistency with functional and behavioral descriptions can be hold. In addition, these properties should be represented by a meta-model suited for computational synthesis, but this step will be handled in future publications.

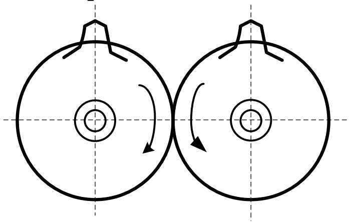


Figure 3: Properties of a design object structure

Vocabulary of elements is the end result of a conceptual design phase, and is, therefore, known when performing a design definition activity. Configuration and description of the elements are, however, still to be formalized.

Configurations can be inferred from an FBS representation of the conceptual design. They emerge from the behavioral representation of the design object and can be translated into two types of relations:

- Topology relations expressing the connectedness of the elements. They can be expressed by means of sentences like: *is_connected_to*, *is_next_to*, *belongs_to*, etc. In future work it will be illustrated how such relations can be translated into Region Connection Calculus (a topological theory based on spatial region ontology), so that computational models can be formulated.
- Element constraints, also regarded as physical coherence constraints, derive generally from a behavior common to all design objects: *to_keep_physical_integrity*. This behavior draws from the fact that the activity of designing is carried out with the expectation that the designed artifact will operate in the natural world and the social world. Element constraints can be expressed in a sentence wise form: *do_not_share_spatial_location*, *is_larger_than*, *is_smaller_than*, etc. When element descriptions are available, mathematic representations can model them.

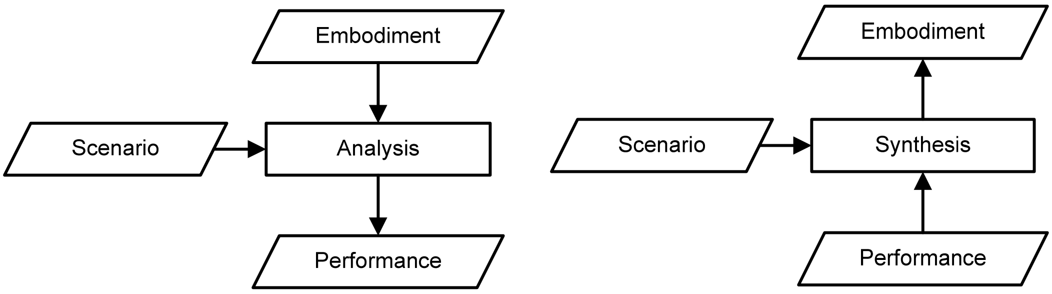
3.2 Analysis and synthesis information flow

Descriptions of the vocabulary, in the form of parameters and the relations among them, have also to be formalized before a parametric design process can take place. An analysis based design exploration, developed by Schotborgh et al [20] is therefore used. The information flow around an analysis technique can be categorized in three groups: embodiment, scenario and performance, as shown in [20]. Embodiment regards the set of parameters describing the design object elements, topology and properties. The scenario is related to the set of entities describing the flow of energy, mass or information the embodiment is exposed to. Performance determines how the embodiment behaves under a certain (group of) scenario. These entities, later on regarded as parameters, are constraint to assure physical integrity and avoid physical impossibilities.

From here it follows that an analysis technique for a parametric design problem allows the quantification and qualification of the performance of an embodiment undergoing a given scenario, as shown in Figure 4(a). This categorization shows synthesis as the process where embodiment parameters are specified aiming at meeting a group of performance parameters under the presence of a given scenario, as shown in Figure 4(b). Design rules have an inverted effect to analysis, since scenario and/or performance parameters allow instantiating embodiment parameters.

Having described these concepts, it can be summarized that:

- The groups of parameters describing the elements of a Structure are: embodiment parameters, scenario parameters and performance parameters.
- Analysis techniques allow quantifying the accomplishment of the design object expected behaviors.
- Design rules, when existing; allow using scenario and performance knowledge to make statements of the embodiment.



(a) Analysis *(b) Synthesis*

Figure 4: Information flow of analysis technique and synthesis process

3.3 Conclusions

The previous analysis allows concluding that the information contents required for defining a parametric design problem are: (1) topologic relations, (2) physical integrity constraints, (3) embodiment, scenario and performance parameters, (4) analysis techniques and (5) design rules. These results are used in section 5 to develop a methodology to aid the assessment of this information in a given design problem. The methodology is demonstrated for the case study presented in section 4.

4 CASE STUDY

This paper forms part of the research project Smart Synthesis Tools being developed at the University of Twente in cooperation with Delft University of Technology, both in The Netherlands. The project researches the development process of new synthesis tools aiming at delivering a generic development methodology for dedicated synthesis tools supporting industrial design processes [21]. The development of a synthesis tool for the automated generation of cooling channels layouts for injection molding has been selected as one of the projects case studies.

Cooling systems for injection molding are defined as the set of components that enable heat transfer between a hot melt contained in a mould and a coolant substance flowing within it. Cooling systems allow reducing the time required for solidifying the plastic melt, which is translated in manufacturing cost reduction. In addition, cooling systems should be capable of delivering uniform temperatures on the plastic part so that unwanted effects, such as differential shrinkage and warpage, can be minimized. A cooling system for injection molding is composed of a temperature-controlling unit, a pump, coolant supply manifold, hoses, cooling channels, and collection manifold. For the present case study, the cooling channels layout design has been selected from the other components, as it determines to a great extend the performance of the cooling system. Sliders, ejectors pins and other mould moving parts constraining the mould volume make it hardly feasible to design optimal cooling layouts.

Different research can be found on the engineering design literature concerning the automated design of cooling systems for injection molding. Li et al. [22] used graph theory to develop a computational tool for the automatic layout design of plastic injection mould cooling systems. A graph structure was build for capturing defined preliminary designs, while a graph transversal algorithm is employed to generate candidate cooling circuits from the graph structure. Heuristic search was used to develop the candidate solutions into layout designs that contemplate tentative manufacturing plans. He et al. [23], develop an intelligent system for molding parameters resetting using fuzzy logic coupled with neural networks. Fuzzy logic provides an inference morphology that enables approximate human reasoning capabilities to be applied to knowledge-based systems. The trained network is able to predict not only what parameter to adjust, but also the magnitude of adjustment based on the part, mould, and defects description. Park et al. [24] developed an optimization procedure of the injection molding cooling system to minimize a weighted combination of the temperature non-uniformity over the part surface and the cooling time related to the productivity with side constraints for the design reality. An algorithm for obtaining optimal designs was developed from the special boundary integral formulation and the sensitivity analysis formulation.

5 FBS BASED DESIGN EXPLORATION

The goal of FBS Based Design Exploration is to define the set of elements together with their description and configuration, representing a given parametric design problem. These have been categorized in Section 3, resulting in embodiment, scenario and performance parameters serving as entities, while topology, constraints, analysis techniques and design rules serve as the relations. The methodology uses FBS modeling for assessing the Function, Behavior, Principle, State and Structure representation of the design object in question. States are used for deriving performance and scenario parameters, while embodiment parameters are defined by relating performances and scenario to a given analysis technique. In Figure 5, the different steps are presented together with the information flow.

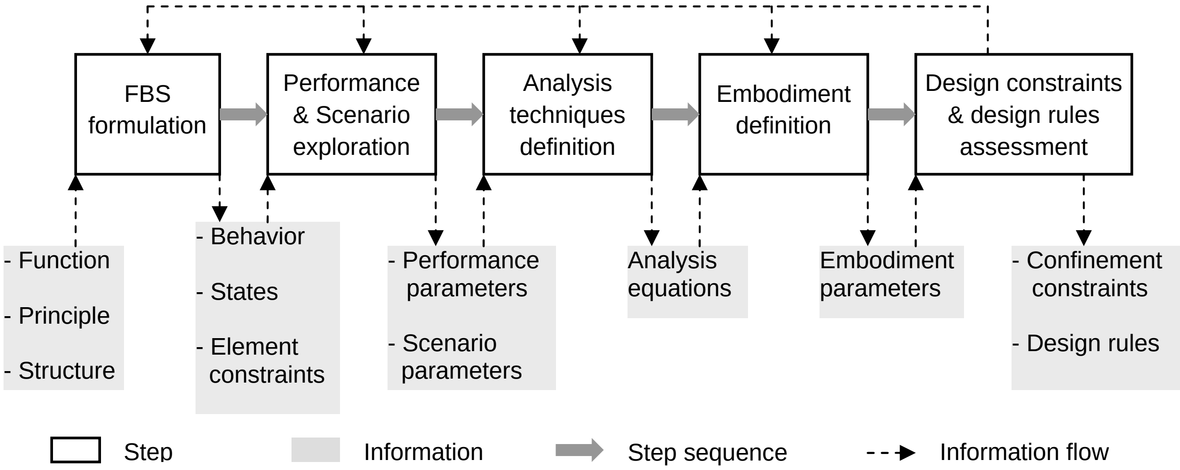


Figure 5: Steps and information flow in the PBDE methodology

5.1 FBS formulation

FBS modeling is the first step that is proposed in the design exploration phase for defining a design problem parametrically. Functions, Structures elements and Principle are known instances when dealing with conceptual designs artifacts, becoming input for the FBS formulation. Then, by human mapping, Behaviors allowing the Function to exist are formalized. The (sequence of) States that the Structure is meant to experience are described by relating the design Structure elements and the found Behaviors to fundamental Principles. Topology relations can be extracted by formalizing the connectedness of the elements in the structure. For the case of cooling system design for injection molding this is illustrated in Figure 6.

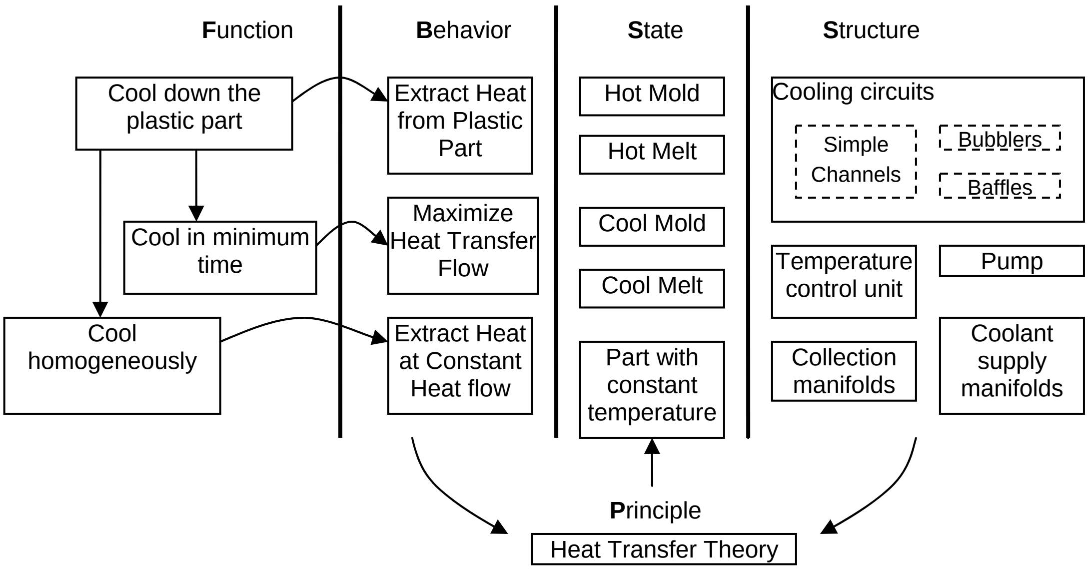


Figure 6: FBS representation of cooling system design for injection molding

The Figure shows how the cooling system Functions are mapped to Behaviors that allow the Function to exist, i.e., *Cool_Down_Plastic_Part* is mapped to *Extract_Heat_From_Plastic_Part*. It also shows how Structure and Behavior are related to the States by means of the fundamental Principle, in this case Heat Transfer Theory. The Structure is composed by several components. However, as stated in Section 4, only cooling channel layout design will be taken into account for the purpose of describing the methodology. Examples of topology relations can be: cooling circuit *is_composed_of* cooling channels, one cooling channel *is_connected_to* one cooling channel, cooling channel *starts_at* mold surface, cooling channel *ends_at* mold surface, cooling channel *is_confined_in* mold, etc. An example of element constraints would be: cooling channel *does_not_share_spatial_location_with* melt.

5.2 Performance & Scenario exploration

Parameters describing the properties of States or sequence of States (regarded in Section 3.1 as State variables) can now be derived from the FBS formulation. For this purpose, physical variables present in both Principle and State serve as entities representing performance and scenario parameters. For the case of injection molding cooling systems, many performance and scenario parameters can be used to describe the different (sequence of) States the system goes through. Table 1 presents a generalized summary of performance and scenario parameters.

Table 1: State-Performance mapping

State	**Sequence**	**State variables**	**Type**
Hot Mold	First	Temperature Mold, Properties Mold	Scenario
Hot Melt	First	Temperature Melt, Properties Melt	Scenario
Cool Mold	Second	Temperature Mold, Properties Mold	Performance
Cool Melt	Second	Temperature Melt, Properties Melt	Performance
Part constant Temperature	Second	Temperature Difference in Part	Performance

The dynamics, implied by the sequence of States, can also be translated into a performance parameter. In this case the difference in time between both states is chosen as performance parameter, representing the time required to cool the hot melt down to ejection temperature. The complete description of performance and scenario parameters can be found in Table 2.

5.3 Analysis techniques definition

Fundamental Principles are assessed in terms of the performance and scenario parameters to define the proper analysis technique. Analysis techniques might be defined at different levels of abstraction. The chosen abstraction level depends on the level of design specification the designer considers appropriate for representing its design problem. The concept of partitions, defined by Gero et al. [15], can also be used to derive different analysis techniques relating different states variables. Partitions embody only some of the attributes of the structure elements, but more than one partition may have the same attributes.

When assessing the analysis techniques two possibilities arises, one in which they are existent, and a second when they have to be derived from the fundamental principle. The formulation of new analysis techniques is beyond the scope of the paper.

Consider the case of the cooling system design for injection molding. A simple analysis has been chosen from [25]. The analysis is derived from the conduction heat transfer equation for a substance in rest under several assumptions. More details can be found in [25]. The analysis consists of the following calculation:

- Calculate heat transfer from the melt to the cooling medium using equation (1).
- Calculate the shape factor (S_e), Reynolds (Re) number, the coolant heat transfer coefficient (α) and the thermal diffusivity of the melt (a) using equations (2), (3), (4) and (5) respectively.
- Consider $Q_{abs} = Q_m$, and use results of (2), (3), (4) and (5) to solve the system composed by equations (6) and (7).

The set of equations (1) to (7) represent the analysis technique that has been chosen for the purpose of demonstrating the methodology. Each one follows from different partitions, obtaining that different parameters appear in different analysis equations. The analysis has been formulated in such a way that it holds at both sides of the axe of symmetry shown in Figure 7. This allows assessing the temperature difference between the two sides of the mould, which was selected as performance parameters in Section 4.2. It is worth mentioning that 3D analysis formulation is better suited for the performance calculation of this type of problems [26]. However, to describe the performance and scenario parameters so far considered, the analysis technique here presented suffices. Table 2 presents a list with the description of the used symbols.

$$Q_{abs} = 10^{-3} \cdot \left[(T_M - T_E) C_{ps} + i_m \right] \cdot \varsigma_m \cdot \frac{s}{2} \cdot x \tag{1}$$

$$S_e = \frac{2\pi}{x^4} \cdot \left[\ln\left(2 \cdot x \cdot \sinh\left(\frac{2 \cdot \pi \cdot y}{x} \right) \middle/ \pi \cdot d \right) \right]^{-1} \tag{2}$$

$$\mathrm{Re} = \frac{10^{-3} \cdot u \cdot d}{v} \tag{3}$$

$$\alpha = \frac{0.031395}{d} \cdot \mathrm{Re}^{0.8} \tag{4}$$

$$a = \lambda / \varsigma \cdot C_p \tag{5}$$

$$t_k = \frac{10^{-3}}{Q_m} \cdot \left(\frac{1}{\lambda_{st} \cdot S_e} + \frac{1}{\alpha \cdot 10^{-3} \cdot 2 \cdot \pi \cdot R} \right)^{-1} * \left(T_W - T_{water} \right) \tag{6}$$

$$t_k = \frac{s^2}{\pi^2 \cdot a} \cdot \ln\left(\frac{4}{\pi} \cdot \frac{T_M - T_W}{T_E - T_W} \right) \tag{7}$$

5.4 Embodiment definition

The analysis technique can now be used to define the parameters describing the embodiment for the chosen abstraction level. This is done by selecting the set of parameters present in the analysis that describe topological and geometrical characteristics of the structure. For the case of the cooling system design, the embodiment parameters have been depicted in Table 2, and are sketched in Figure 7.

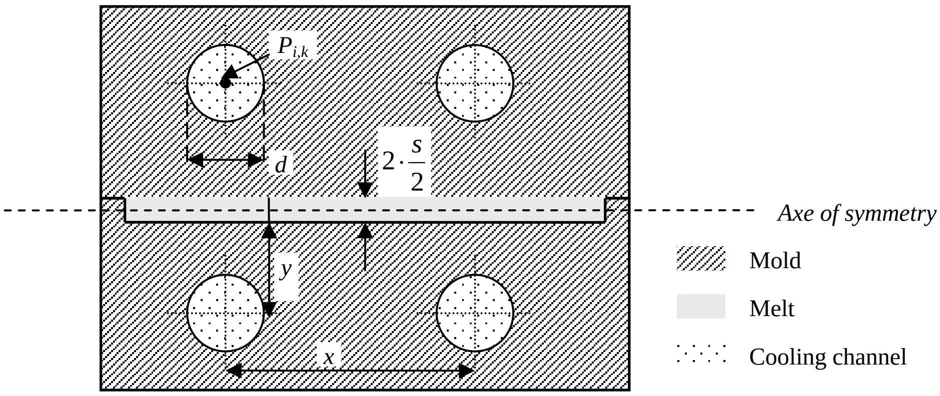


Figure 7: Cooling channel layout scheme

5.5 Design constraints and design rules assessment

Once the performance, embodiment and scenario parameters have been identified, the constraints and design rules can be formalized. Element constraints (Section 3.1) can now be represented mathematically by relating the found parameters. Confinement constraints can also be stated by defining the ranges where the embodiment can exist. Confinement constraints are meant to avoid physical impossibilities by confining the parameters between limits the designers considers appropriate, depending often on experience. To specify design rules, knowledge has to be assessed. Counting with the parametric description and constraints, can aid the process of extracting knowledge from diverse sources, like design books, experts and internet.

For the case of cooling channels layout design, some examples are:

- The topologic relation, cooling channel *is_confined_in* mold, can be modeled by equation (9)
- Element constraint avoiding two cooling channels sharing the same space in equation (10)
- Confinement constraint determining the range of the Reynolds number is equation (11)
- Design rule defining the diameter of the cooling channel as function of the part thickness in equation (12).

$$P_{i,k} \in \text{Mold} \tag{9}$$

$$\sqrt{\left(x_{i,k} - x_{i,k+1}\right)^2 + \left(y_{i,k} - y_{i,k+1}\right)^2} - \frac{\left(D_K + D_{k+1}\right)}{2} \leq \zeta_1 \tag{10}$$

$$10000 < \text{Re} < 120000 \tag{11}$$

$$\zeta_2 \leq D \leq \zeta_3 \tag{12}$$

Note that the symbol ζ_i is used for representing a border value, while the word Mold represents the element mold.

Table 2. List and description symbols used in the analysis technique

Symbol	Units	Description	Classification
Q_{abs}	KJ/m	Heat content of melt	Scenario
Q_m	KJ/m	Heat absorbed by coolant	Performance
t_k	s	Cooling time	Performance
S	mm	Part thickness	Scenario
X	mm	Distance X	Embodiment
Y	mm	Distance Y	Embodiment
D	mm	Diameter of cooling channel	Embodiment
R	mm	Radius of cooling channel	Embodiment
$P_{i,k}$	(mm,mm)	Point *i* of cooling channel *k*	Embodiment
i	N^o	Index: 1 is star and 2 is end point of cooling channel	Embodiment
k	N^o	Index: 1…N cooling channel	Embodiment
T_M	^oC	Melt (Molding) temperature	Scenario
T_E	^oC	De-molding temperature	Performance
T_W	^oC	Temperature of mold	Performance
T_{water}	^oC	Temperature of cooling water	Scenario
i_m	KJ/Kg	Latent heat of fusion of the polymer	Scenario
C_{ps}	KJ/(Kg K)	Specific heat of the polymer	Scenario
ς	g/cm^3	Mel density	Scenario
a	cm^2/s	Thermal diffusivity of the melt	Scenario
V	m^2/s	Kinematics viscosity of water	Scenario
U	m/s	Velocity of cooling water	Scenario
λ_{st}	W/(m K)	Thermal conductivity of mold steel	Scenario
C_p	KJ/(Kg K)	Specific heat of water	Scenario
λ	W/(m K)	Thermal conductivity of water	Scenario
α	W/m^2 K	Heat transfer coefficient	Scenario
t_k	s	Cooling time	Performance

6 FURTHER WORK

As it was mentioned in the introduction, design exploration is the first phase of what has been defined as parametric design definition. Further research work will focus on structuring the design problem in smaller pieces and creating a meta-model of the design. It is also worth mentioning, that the formalization of the States using the FBS formulation remains weak. Performance parameters, followed by scenario and embodiment parameters, derive directly from the description of the States the Structure experiences. Therefore, further research is required to identify systematically the (sequence of) States to avoid unexpected Behaviors of the design object.

Design structuring can be done by defining three structuring dimensions: abstraction, components and parameters. The first dimension is about the different abstraction levels at which analysis techniques can be formalized. Component dimension is about how groups of embodiment parameters fulfill specific design Behaviors. The parametric dimension deals with the mathematical affinity between design parameters. Understanding this affinity can allow the implementation of constraint solving techniques to assist the synthesis process. At last, creation of meta-models containing the design structure and parametric representation can serve as road maps for synthesis algorithms development and computer implementation, which is the long term view of the present research.

7 CONCLUSIONS

This paper presented the definition of parametric design problems as the first step towards a common framework for the methodological development of computational synthesis tools for parametric design problems. Three main processes were identified its accomplishment, namely, design exploration, design structuring and model development. Design exploration was further investigated, with the aim of answering the following questions: What sort of information content is required for the definition of such a parametric model? How can this information be assessed for a given design problem?

The required information content was concluded in section 3.3 to be conformed by: topologic relations, physical integrity constraints, embodiment parameters, scenario parameters, performance parameters, analysis techniques, confinement constraints and design rules. Furthermore, a methodology for design exploration was also presented. The method allows identifying the information contents when being exposed to a given parametric design problem, and was described by means of a case study, namely, design of cooling systems for injection molding.

The results of this research have been successfully applied for some parametric design problems. However, more experiments are required to verify this research finding. It is thought, that defining parametric design problems as proposed here can be helpful in developing solution approaches for the computational synthesis problem.

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