



KBE approaches in preliminary design: a case study

M. Caneri ^(a), G. Concheri ^(a), R. Meneghello ^(a), A. Baschiera ^(a)

^(a) DAUR – Laboratory of Design Tools and Methods in Industrial Engineering, University of Padova.

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Corresponding author:

Massimiliano Caneri
Tel.: +39 049 8276734
e-mail:
massimiliano.caneri@studenti.unipd.it

Abstract

Purpose:

Purpose of this work is to summarize some possible improvements to the traditional parametric approach for virtual prototyping, by illustrating a particular application case: the preliminary design of a heat recovery system. Reference is made to the following scenario: conceptual design being accomplished, the team of designers has to face problems typical of system design, e.g. assigning a common value for variables to establish some guidelines, or evaluating alternative solutions. In such a case, a fast, flexible way to generate many versions of the same feature could be profitable.

Method:

Fast evaluation of alternative solutions will be accomplished by using the knowledge-based capabilities of one of the most popular CAD platform, Catia V5. A simplified predictive model of the thermo fluid dynamic behavior of the heat recovery circuit, based on a computing worksheet, will be interfaced with the CAD by a project table: in this way, all the current values assigned to the degrees of freedom will be transmitted to the virtual prototype. The CAD model will be featured with some checks, rules and automatic procedures: hence, it's possible to select all the configurations compatible with some imposed constraints, and save them in a new project table, to easily recall and transmit them to project partners.

Result:

Through the model it was possible to find, select and automatically reconstruct all the configurations (defined by combinations of values for degrees of freedom) compatible with the imposed constraints.

Discussion & Conclusion:

The use of the knowledge base capabilities of the Catia V5 platform, and the interface with a scientific computing software by a project table, allowed the development of automatic procedures to evaluate the alternative configurations of a heat recovery system and check their compatibility with specific requirements.

1 Introduction

In a typical scenario during the design of complex systems, after the early conceptual phase of a project, characterized by technology and component type selection, designers must establish some specific requirements and compare alternative solutions to meet them. Therefore, they need some methods to ease and fasten this process. Virtual prototyping is one possible strategy; in particular, a parametric approach can be profitable: it makes possible to change values of parameters and evaluate their impact on product functionality. However, implementing a Knowledge Based approach can bring further improvements, especially when a team of specialized designers must cooperate at the same project: in fact according to Lovett and others [1], "a knowledge-based system (KBS) is the one that captures the expertise of individuals within a particular field (the "domain"), and incorporates it and makes it available within a computerized application". The same authors distinguish the functionalities of KBE ("Knowledge Based Engineering") applications in three categories:

- Geometry (built-in CAD capabilities or CAD-interfacing tools);

- Configuration ("matching of valid combinations of components");
- Engineering knowledge, enabling "manufacturing and other considerations to be built into the product design".

Cugini et al. [2] and Rosen et al. [3] focus on the problem of taking into consideration different criteria in Product Development Process ("PDP"), regarding functional, technological and other aspects: in fact, the optimization cycle of virtual models often cause the loss of related information, resulting in products which may be too expensive, or not manufacturable, or violate design constraints, standards or functional aspects. This loss of information leads the designer to "model the geometry again interpreting the results obtained by the optimization process, and considering standards and manufacturing features and constraints".

Cooper and La Rocca [4] stated "KBE was originally a tool for the research laboratories of deep-pocketed companies", therefore "for roughly 20 years, KBE has been applied to challenging design and engineering problems, mainly in capital-intensive industries such as automotive, civil engineering and, especially, aerospace". The reason to this poor diffusion is mainly due to high cost and technical effort, which become reasonable only in the

described scenario. However, latter improvements in computer technology made the diffusion of KBE methodology more suitable in less complex projects. In this work, a fast and simplified KBE application to a specific case study is proposed, with particular regard to:

- compatibility checking of a set of parameters values (defining a “configuration” of the system) with system requirements;
- managing different configurations with one single parametric virtual prototype, through project tables and catalogues, making the creation of different models unnecessary;
- storing different and acceptable configurations automatically, making them accessible for further operations;
- creating adaptive virtual prototypes, available in several configurations, to match different functional conditions.

2 The case study: a Heat Recovery System

The case study concerns a Heat Recovery System for a mCHP (micro Combined Heat and Power) system. Fig. 1 illustrates a possible layout. Please note the presence of a heat recovery circuit for lubrication fluid (SAE 10W-30 oil in this case): in detail, it can be essentially schematized by a heat exchanger and a circulator (pink-highlighted subsystem). This work concerns with a simplified, integrated procedure for sizing both of them, and automatically select and store acceptable configurations, for further operations. Note that the results of conceptual design and technology selection will be assumed: in particular, some component parameters will be considered as imposed.

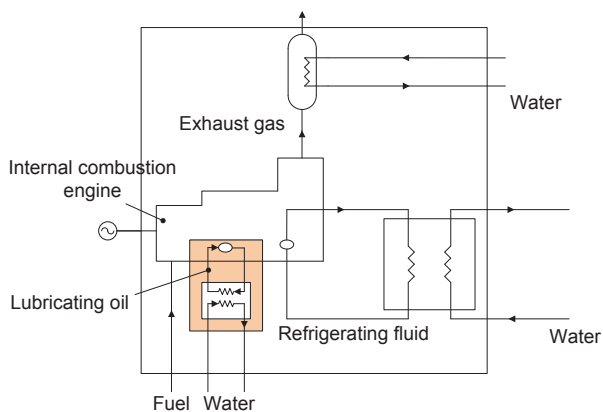


Fig. 1 Example of mCHP layout

2.1 Plate Heat Exchanger

It is assumed that the previous conceptual design had led to the selection of a chevron-type plate heat exchanger (see Fig. 2). Material is AISI 316, while plate parameters are the following [6]:

- a : amplitude of sinusoidal corrugation
- Λ : pitch of corrugation
- α : chevron angle
- L, w, b : length of plate, width of plate, distance between two consecutive plates (m)
- s : plate thickness
- N : number of plates

All values of the above parameters are imposed, except for the number of plates: therefore, it will be considered

as a degree of freedom, defining the possible configurations of the system.

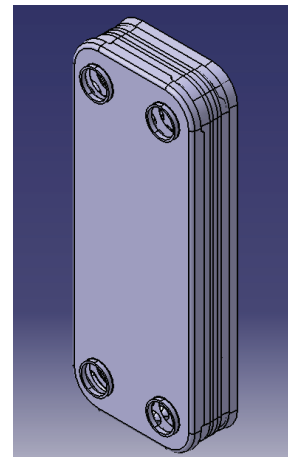


Fig. 2 Plate Heat Exchanger

2.2 Pump

The pump is the other main component of the heat recovery circuit. Suppose that the previous conceptual phase imposed a centrifugal pump; the geometry and the dimensions of the impeller are set. The geometry of the volute is influenced by fluid volume flow and by geometry (and angular velocity) of the impeller [7]. Therefore, two types of volute geometry can be adopted:

- a) Rectangular section with logarithmic spiral profile;
- b) Circular section with exponential spiral profile.

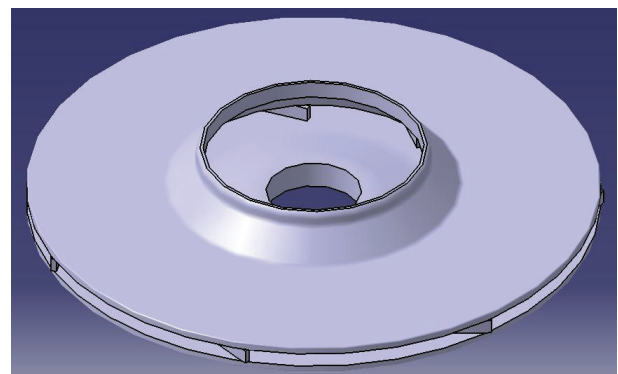


Fig. 3 Impeller

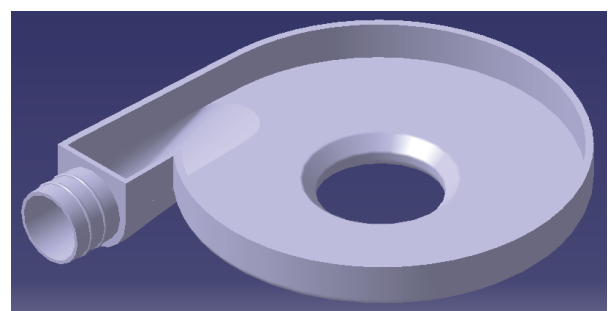


Fig. 4 Volute with rectangular cross section

Fig. 3, Fig. 4 and Fig. 5 illustrate a virtual model of the impeller and of the two volutes.

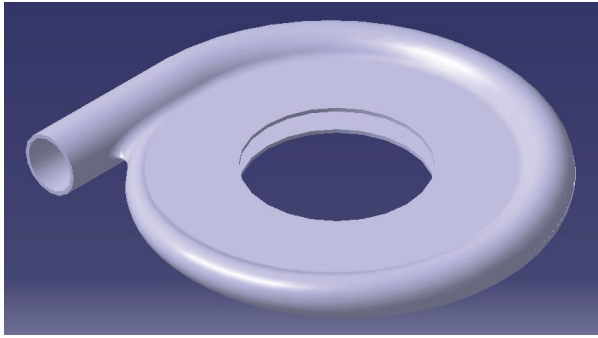


Fig. 5 Volute with circular cross section

2.3 Targets and constraints

This section describes in detail the targets and the imposed constraints.

2.3.1 Targets

Suppose a certain heat flux through the heat exchanger must be obtained, the hot fluid being the lubricant (SAE10-W30) and the cold one being water. The values of temperature of the two fluids are imposed or calculated (see the “Heat Flux Model” at par. 3.1), and so the volume rate of water: in this case, being the plate geometry already set, only two parameters remain unset: oil volume rate (“ Q_{oil} ”) and number of plates (“ N ”). Naturally, the entity of heat transfer depends on both parameters. Consider also their influence on hydraulic loss, that influences the choice of the circulator: provided the geometry, one degree of freedom is represented by angular velocity of the impeller (or by the number of electric poles). Both volume rate and rotational velocity affect the geometry of the volute, influencing the profile [7]. Moreover, another degree of freedom considered in this case study is volute geometry, as described in 2.2. Beyond technical aspects, also economical ones should be considered: an increase in plate number leads to increased costs.

Finally, the target is to identify and collect several set of values (for volume flow rate, N , number of poles or rotational speed, geometry of the volute) which define the configurations compatible with constraints, described in next paragraph.

2.3.2 Constraints

Paragraph 2.3.1 describes the target, the parameters which define the system configurations and their relations. With regard to the acceptability criteria for configurations, they are:

- 1) The difference between the obtained heat flux and the target one must be lower than a specified value.
- 2) The size of the pump must be compatible with a specified limit.
- 3) The cost of the heat exchanger must be lower than a specified value.

3 Methods

In this section, methods used to reach the target will be discussed. The scheme of Fig. 6 illustrates the model implementation.

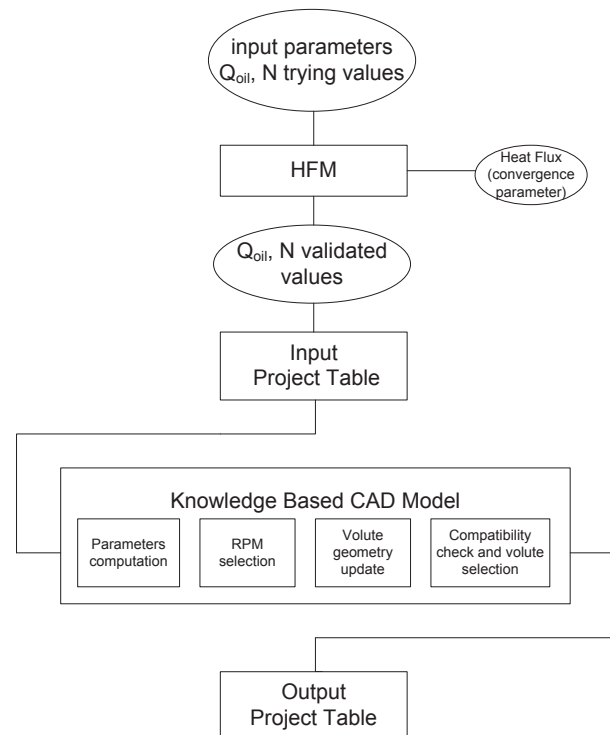


Fig. 6: Model implementation

First, some parameters, inputted by user, are elaborated by a thermodynamic system model, implemented in a computing worksheet (HFM, “Heat Flux Model” in figure), which allows a first validation of free project parameters. Then, the validated values are transferred to the knowledge-based CAD model (via an Input Project Table) capable of refining the selection of acceptable configurations. Last, only the validated ones are saved in an Output Project Table. The following paragraphs describe, in detail, the construction of the reported scheme, by the following steps:

- 1) The implementation of the HFM, to obtain values of temperature of inlet and outlet fluid;
- 2) The construction of a parametric model for the impeller, the volute and the heat exchanger;
- 3) The integration of the CAD model and the HFM.

3.1 The Heat Flux Model

The system shown in Fig. 1 has been schematized like a set of I/O blocks. Each block features inlet and outlet values for temperature and flow rate. All blocks present only one input and only one output, except for heat exchangers, which are involved by two fluids.

In general, for two blocks linked in serial configuration, inlet values of variables of the second block are equal to the outlet ones of the previous block (i.e. same value for both flow rate and temperature).

The model created contains all relations to predict inlet and outlet temperature values for each block, while heat flux and flow rate are imposed (their value being suggested by experience chosen on a statistical base).

The model was based on the first law of thermodynamics and on state laws for the involved fluids [5] [8]; it has been implemented in Microsoft Excel, defining the physical model by VB functions.

The same worksheet was used in sizing the plate heat exchanger through Martin's method [6]: in this case the input data are plate characteristics (see section 2.1), while the output ones are the heat flux and the pressure drop. The last one was calculated by extracting the friction factor through interpolation of values in the range of interest.

The model functioning is as follows (Fig. 7): the degrees of freedom are oil flow rate (" Q_{oil} ") and number of plates (" N "). All other data are imposed; in detail, " q_{blocks} " stands for imposed heat flux for already sized blocks, while " T_{ef} " indicates all imposed temperatures, such as for external fluids or hot spots. The HFM provides " T_{he} ", " q_{he} " and " h_{req} " (respectively fluid temperatures, transferred heat flux and head loss in the plate heat exchanger). Varying Q_{oil} and N , q_{he} must result into an imposed range: user must verify convergence manually. In case q_{he} doesn't match system specifications, user must change Q_{oil} and N tentative values. Conversely, there are no limitations on h_{req} .

Please note the proposed method is not fully automatic, since it requires the user to input some sets of tentative values. However, this procedure is preferable to a fully automatic one, for two reasons:

1. A fully automatic one requires the implementation of an iterative computation procedure to manipulate the non-linear Martin's method;
2. The imposition of parameters is more profitable if it's made according to user's knowledge: in fact, the sensitivity to typical values for involved parameters is the first strategy to seek and select only relevant solutions in a fast way.

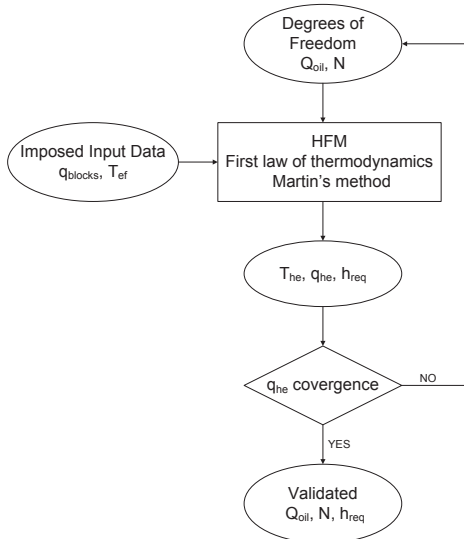


Fig. 7 HFM functioning chart

3.2 Parametric models

All geometries have been created in Catia V5 platform. Details are provided in next paragraphs, with special regards to parametrization logic.

3.2.1 Impeller

The geometry of the impeller is illustrated in Fig. 3. Impeller parameters can be distinguished in different categories, like described in Fig. 8. This scheme is useful to understand the model functioning, too. Geometric characteristics have been specified explicitly, since they are treated as imposed data, then they belong to "Geometric imposed" category in figure. "Otherwise imposed data" category presents a remarkable subset, named "HFM": this one contains all HFM output data, which allow the worksheet to communicate with CAD model. "Calculated parameters" pertain calculations of fluid dynamics quantities and angular velocity of the impeller. They are Part User Parameters defined with formulas, automatically updated when values of (imposed) parameters upon which they depend change.

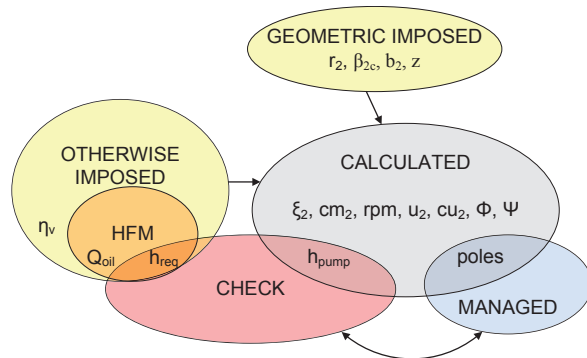


Fig. 8 Impeller parameters classification

All Calculated Parameters are involved in the CAD model internal functioning, but not in I/O operations. Now, please consider "Check" and "Managed" parameters categories: they present some intersections with other subsets: in fact, there are some parameters which belong to more than one set. Their meaning and use can be understood referring to Fig. 9.

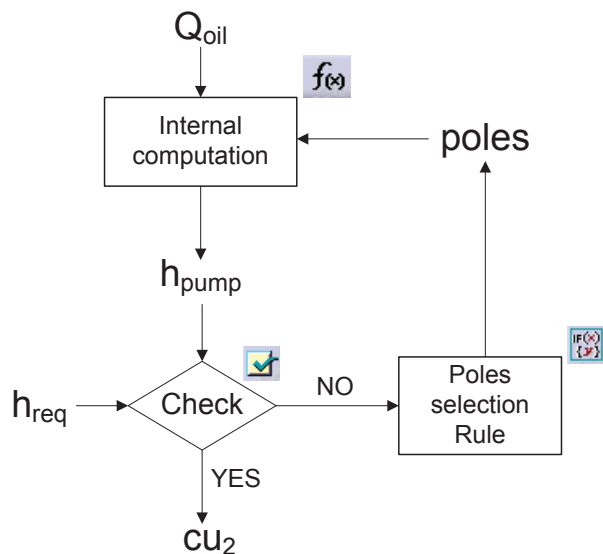


Fig. 9 Impeller parameters usage

" h_{pump} " is the head provided by the pump; it's a "Calculated Parameter" which directly depends on " ψ ", the pressure number of the pump. It belongs to the "Check Parameters" category too: in fact, a "Pressure Drop Check" has been defined to compare h_{pump} with " h_{req} "; the

last one is an output parameter of the HFM (as it can be seen in Fig. 8). The condition to be checked is:

$$h_{pump} \geq h_{req} \quad (1)$$

which is verified when the head provided by the impeller is sufficient to compensate the circuit head loss. Note this one has been considered equal to plate heat exchanger loss, since it represents the larger amount of pressure drop.

Considering the last category of parameters, the “Managed” ones, the only parameter which belongs to this set is “poles”, the number of poles of the electric engine which moves the impeller. This parameter directly affects “rpm”, i.e. the rotational speed of the impeller. Its variation will definitely cause a change in h_{pump} , so a “Poles Selection Rule” has been defined: in particular, it automatically chooses the correct number of poles to obtain a sufficient h_{pump} with the minimum rpm required. After the selection loop, the “Pressure Drop Check” should be verified: if not, this signifies the impeller is not appropriate, even at the max rotational speed. The “ cu_2 ” parameter which is visible in Fig. 9 is one of the “Calculated Parameters”: it’s used like an input parameter for automatic volute creation.

Ultimately, the described parametrization doesn’t affect the geometry of the impeller: its purpose is to choose the minimal appropriate rotational speed which grants, with the given geometry, the required head. This choice provides also one of the parameters (cu_2) which are required to create an appropriate volute.

3.2.2 Volute

Like for the impeller, volute parametrization will now be discussed. One basic difference with respect to the previous one, is that now geometry will be affected and automatically updated according to values imposed or calculated for parameters. Moreover, automatic selection of volute type will be implemented: the circular cross section one will be considered as preferable, however it’s less compact than the rectangular cross section one: so, a dimension check and a rule will be used to select the correct geometry.

First of all, consider again parameters distinction, this time with respect to volute (Fig. 10).

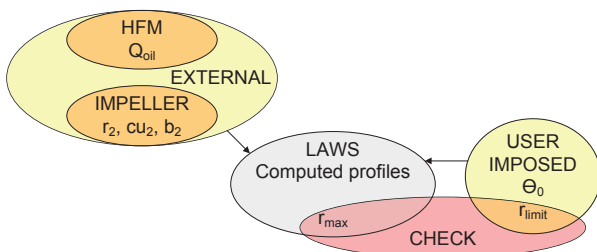


Fig. 10 Volute parameters classification

Some “External” input parameters are again present; they are not defined internally of the part: in fact, they come from either the HFM or the impeller parametrization. Again, these kind of parameters are not calculated nor managed: they are imposed. For a better description of other categories, please consider Fig. 11. The “Laws” set refers to internal parameters of the part which are obtained through the evaluation of some defined Laws; in particular, they allow to compute volute profiles: the

rectangular cross section volute can be generated from the exact profile, while the circular cross section one can be easily created through a multi section surface, which fits an appropriate number of computed cross section profiles. Input data for calculation come from the above-described “External set”. This phase of procedure is represented by the first rectangular block in Fig. 11, where the employment of Formulas and Laws is declared. Computation of the entire volute profile allows for the evaluation of “ r_{max} ”, the maximum radial distance of the volute from the axis. This parameter belongs to both “Laws” and “Check” sets: in fact, its value will be used to check geometric compatibility of two volutes, through the comparison with the “Check” and “User imposed” “ r_{limit} ” parameter. The last one is a design constraint (see section 2.3.2). The mentioned volute selection procedure executes the geometry check for both volute types and is managed through a Rule, whose behavior is explained in Fig. 12.

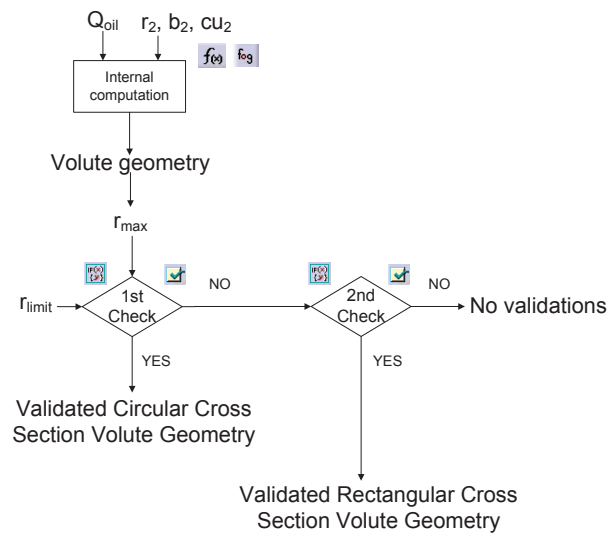


Fig. 11 Volute parameters usage

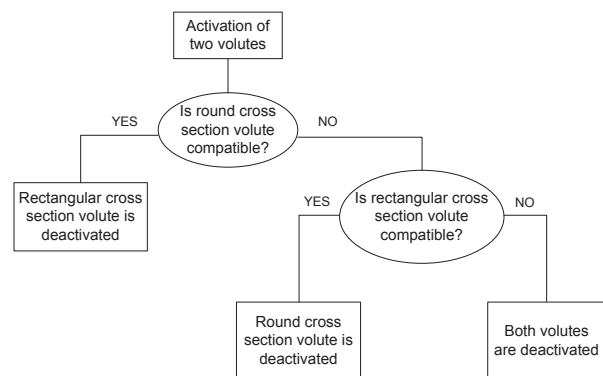


Fig. 12 Rule functioning

The rule functioning can be described through the following steps:

1. Both volutes are activated (and automatically computed thanks to the described parametrization and defined Laws);
2. The geometry compatibility check is applied to the round cross section volute: if its result is “True”, the volute is validated, therefore the other

one can be deactivated; otherwise, circular cross section volute cannot be validated, and it must be deactivated; the Rule will proceed with a second check;

3. A second geometry compatibility check is applied: this time, the rectangular cross section volute is evaluated. If check result is "True", the volute is validated and selected for an acceptable configuration. Otherwise, there aren't acceptable configurations.

3.2.3 Plate Heat Exchanger

The model of Fig. 2 has been parametrized with the following method: first of all, a User Parameter ("N") was created, which stands for number of plates. Since there are two kinds of plates, which are alternately disposed, the heat exchanger can be constructed by two different rectangular patterns, one for each kind of plate. The number of iterations of the two patterns can be associated to an User Parameter, for example $N_1 = N/2$. However, to allow odd values for N, two parameters will control the number of iterations: one for each kind of plate. In this case, they can be defined like follows:

$$N_1 = \text{ceil}\left(\frac{N}{2}\right) \quad (2)$$

$$N_2 = \text{floor}\left(\frac{N}{2}\right) \quad (3)$$

where *ceil* and *floor* are rounding up and rounding down functions, added to parameters in the formula contextual menu. Please note that N is one of the input parameter of the model, like stated above.

At last, one further User Parameter, "Cost", will be defined: it represents the total cost of plates, whose expression can be set as follows:

$$\text{Cost} = c_1 + N \cdot c_2 \quad (4)$$

where c_1 is a fixed quote and c_2 is the amount proportional to plates number N. The definition of Cost allows to impose the Cost Check: the condition to be verified is:

$$\text{Cost} \leq \text{Cost}_{limit} \quad (5)$$

Again, the check will be managed by a Rule (Fig. 13).

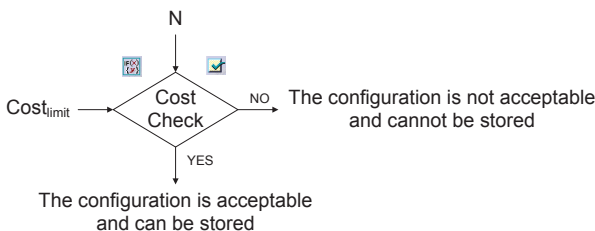


Fig. 13 Plate heat exchanger parameters usage

There are two imposed input parameters: N, which comes from the HFM, and the above defined Cost_{limit} . Note that the Cost Check is performed after volute selection and validation: this signifies that if Cost Check is passed, a configuration matching technical requirements will be stored as acceptable; if not, such a configuration will be rejected, even if technically approved.

3.3 Interfacing CAD with HFM

Finally, the functioning of the entire model will be considered. See Fig. 14.

Meaning and interactions of all blocks have been previously discussed, except for the two light blue-highlighted ones: they deal with interactions among Knowledge Based CAD model and I/O files. In particular, as stated above, an Input Project Table has been employed to receive HFM output data and link them to correct CAD parameters, thus allowing for automatic configuration update and evaluation. Similarly, an Output Project Table was defined to store significant parameters to an external file (in .xls or .txt format). This step worths

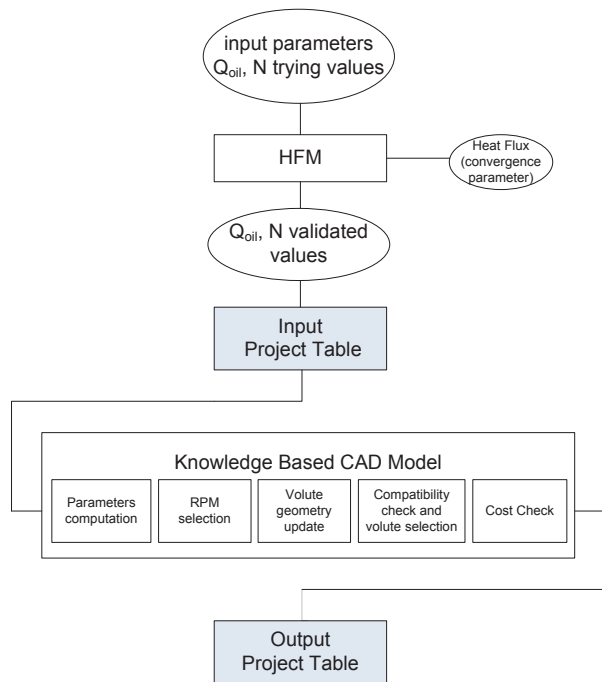


Fig. 14 Entire model functioning

some explanations: in fact, if synchronization of parameters with external input data is always required and fully automatic, output data storing must occur only when needed, and parameters associations are not sufficient to make the procedure automatic. The already explained "Volute Selection Rule", "Pressure Drop Check" and "Cost Check" are capable to select configurations to be stored; in other words, they are sensitive to verification of all system requirements which imply the storage procedure to be launched. However, the storage step has yet to be managed: this can be done by setting a Rule and a Macro (Fig. 15).

The "Storage Rule" considers results of Pressure Drop Check, Cost Check and Volute Selection Rule and acts according to their values: the following different cases can be distinguished:

- 1) Limit of cost is matched, Pressure Drop Check is verified and one of the two volutes is geometry compliant: the actual configuration is stored, saving significant parameters which define it ($Q_{oil}, N, rpm, \text{selected volute}$);
- 2) At least one between Cost and Pressure Drop Checks is not verified: the actual configuration is not saved;
- 3) Both Cost and Pressure Drop Checks are verified, but neither the circular cross section

volute nor the rectangular cross section one are geometry compliant: the actual configuration is not saved.

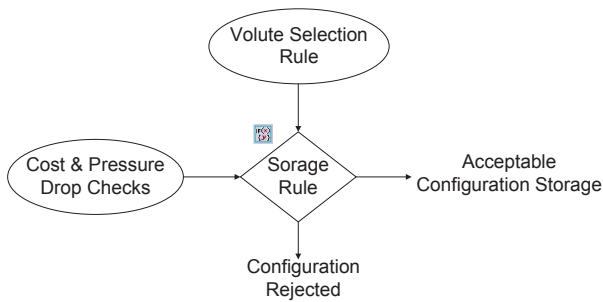


Fig. 15 Storage Rule Functioning

4 Results

The described procedure has been employed to check compatibility of different system configurations and to store relative parameter values in a Design Table. An example is shown below (Fig. 16).

	A	B	C	D
1	Coil (m3_s)	N	rpm (turn_mn)	selected_volute
2	0.0001	14	1455	Rectangular
3	0.0001	14	2910	Circular
4	0.0001	10	1455	Circular
5	0.00015	8	2910	Circular

Fig. 16 Output Project Table linked file

After Output Project Table generation, all compatible configurations can be easily recalled and recreated by selecting them. If desired, the table can be enriched by any other parameter defined in the model.

5 Discussion and Conclusion

A Knowledge Based parametric approach has been applied on a specific case study: the automatic selection of a set of compatible user inputted configurations of a heat recovery circuit. This scenario lies outside the usual application of a KBE approach, primarily addressed to management of part and product catalogues. However, the described application is only a simplified example of knowledge based capabilities, which can be applied to handle more complex geometric models and set of parameters. In particular, a great advantage can be experienced in the management of parameters, constraints and project criteria interaction: the definition of Checks, Laws, Rules and Reactions allows for obtaining a faster and simpler generation of a set of virtual prototypes compliant with system requirements.

The described example covers only a part of Knowledge capabilities of Catia V5: improvements to the presented application could be done adopting functionalities like Power Copy and Part Catalogues. In detail, a rational and methodical arrangement of common references for different parts - to be assembled in a unique product - can lead to automatic and case sensitive part integration: for example, automatic interface recognition, modification and matching can be implemented.

Definition of the presented model was relatively simple and fast, and can be profitable in the previous phase of

design to evaluate similar configurations; however, some modest problems have been noticed in parametric surfaces management, which occasionally led to constraints loss or weak definition. This must be regarded as a problem by a practical point of view, but, conversely, can represent an opportunity to a better understanding and a more profitable usage of a CAD platform.

Appendix

List of symbols

HFM:

- q_{blocks} : imposed heat flux in HFM blocks;
- T_{ef} : imposed temperatures in the HFM;
- T_{he} : computed fluid temperatures in the heat exchanger;
- q_{he} : computed heat flux through the heat exchanger;
- h_{req} : computed head loss in the heat exchanger;

Impeller:

- r_2 : external radius of the impeller;
- β_{2c} : outlet blade angle;
- b_2 : outlet blade thickness;
- z : number of blades;
- $\xi_2 = 1 - \frac{s \cdot z}{2 \cdot \pi \cdot r_2 \cdot \sin \beta_{2c}}$: outlet cross section reduction ratio, where z is the number of blades;
- Q_{oil} : oil flow rate;
- η_v : volume efficiency;
- u_2 : rotor tangential velocity at outlet section;
- cm_2 : throughflow velocity;
- rpm : rotations per minute;
- cu_2 : rotor tangential component of absolute velocity;
- $\phi = \frac{Q_{oil}}{\pi \cdot D_2 \cdot b_2 \cdot u_2}$: flux number of the impeller;
- $\psi = 1 - \frac{\sqrt{\sin \beta_{2c}}}{z^{0.7}} - \frac{\phi}{\eta_v \cdot \xi_2 \cdot \tan \beta_{2c}}$: pressure number of the impeller, where z is the number of blades;
- h_{req} : required head
- $h_{pump} = \frac{\psi \cdot u_2^2}{g}$: head provided by the pump, where g is gravity acceleration;
- $poles$: number of electric poles.

Volute:

- r_{max} : maximum radial distance of the volute from the axis;
- r_{limit} : imposed limit to r_{max} ;
- θ_0 : elementary angle of volute.

Plate Heat Exchanger:

- a : amplitude of sinusoidal corrugation;
- Λ : pitch of corrugation;
- α : chevron angle;
- L, w, b : length of plate, width of plate, distance between two consecutive plates (m);
- s : plate thickness;
- N : number of plates;
- N_1 : number of first type plates;
- N_2 : number of second type plates;
- $Cost$: total cost;
- c_1 : fixed quote of cost;
- c_2 : amount of cost proportional to N ;
- $Cost_{limit}$: limit of cost.

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