Journal of Intelligent Manufacturing, 17, 13–27, 2006
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Feature-based interoperability between design and analysis processes

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Received August 2004 and accepted June 2005

Nowadays, not only the production but also the design of industrial products is subject to severe constraints in terms of time, quality and delay. In order to satisfy these constraints, it is necessary to efficiently integrate the most recurrent tasks of the design process. For a large majority of mechanical products, the integration of mechanical analysis into the design process is one of the most obvious and crucial requirements, particularly during the early stages of design. This article presents an original model of design and analysis process interoperability, based on the concept of *mechanical analysis features* and a semantically rich product model. It is intended to support a variety of typical analysis tasks that are frequently required during the mechanical design process. The authors firstly present a brief survey of CAD/analysis integration approaches in order to position their contribution within this domain. Then, a general structure of analysis features is justified by means of experimental results. In order to highlight the modes of interoperability between design and analysis, the authors detail the main characteristics of the product model upon which the design activity is based. This delineation is followed by a formal description of the analysis features, and a proposition for their organisation in feature catalogues. The authors then consider the implementation aspect for these models, and present a scenario illustrating the benefits and current limitations of their approach. The evaluation of the approach is discussed in the conclusion.

Keywords: CAD, mechanical analysis, design process, feature technology, design-analysis integration

1. Introduction

According to (Jacquet, 1998), designing a mechanical product is a complex process, encompassing several product-modelling domains. In the requirement domain, customer needs are modelled in terms of *service functions* (AFAV, 1998) expected by the customer and *global constraints* to be respected by the product. In the functional domain, the expected product functions are modelled in terms of the functional requirements likely to address the customer's needs. In the technological domain, designers specify technological (or conceptual) solutions, comprised of basic functions, in order to meet the perceived needs. In the technical domain, the designers specify technical solution models, which define the product's concrete components, as characterized by their physical (shapes, dimensions, ...) and technological (tolerances, material properties, ...) characteristics. A product in the technological domain (characterized by conceptual solutions) is described from a mechanical point-of-view as an organization of basic mechanical functions, such as pivot joints, slide joints, universal joints or ball-and-socket joints, for example. However, in the technical

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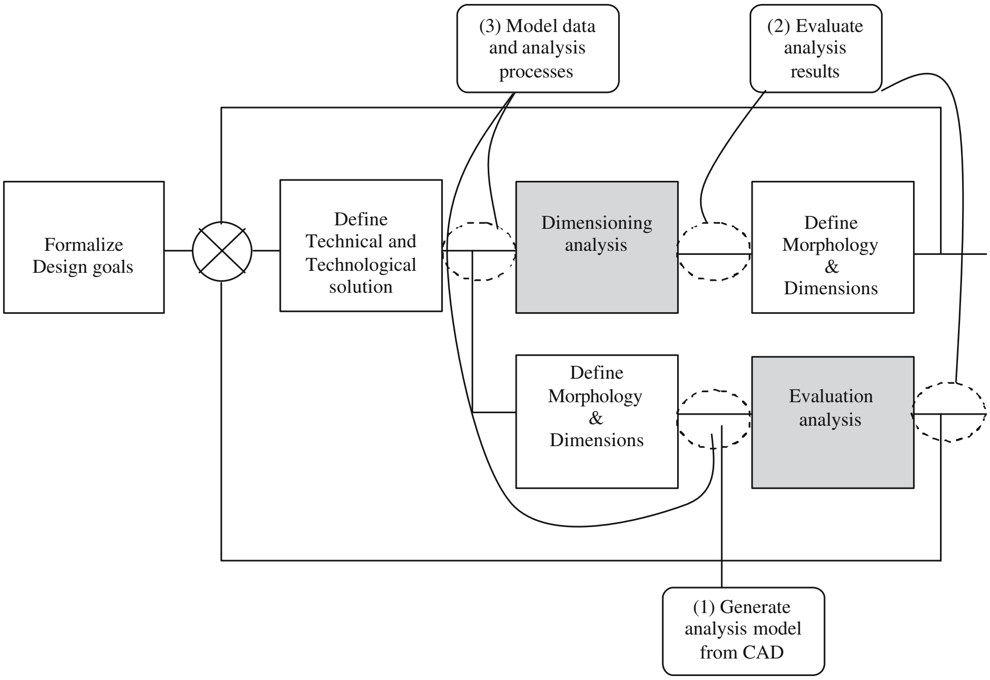


Fig. 1. CAD/analysis interoperability.

domain (characterized by physical solutions), the product is described as an organization of standard mechanical solutions and their corresponding functional surfaces (gears, bearings, slots, ribs, …). A formal description of specific design activities and their corresponding product models has been extensively described in Jacquet (1998).

Mechanical analysis is required to analyse or simulate the mechanical behaviour of the product (Hicks 2002; Roy, 2002), and is used throughout the design process, particularly in the technological and technical domains, where mechanical engineering concepts become more and more explicit. Two types of design-analysis interactions can be distinguished (Fig. 1). The first, *dimensioning*, involves an inverse model of the mechanical problem, and aims at determining the most adequate values for certain product parameters (typically dimensions), given the product constraints. The second, *evaluation*, is appropriate when no inverse model is available and involves a direct model of the mechanical problem. This type of interaction generally involves a trial-and-error approach to determine whether or not candidate values for the various parameters can respect the specifications.

Regardless of the kind of analysis, the analysis process involves a closed loop between the design model (what the designer defines) and the analysis model (what the analyst manipulates), in which the subsequent validations or updates of the design model are taken into account. The degree of mutual integration between the design and analysis models (or the interoperability of the design and analysis processes) determines the time and effort needed to design and validate the product. Moreover, since the design process is not deterministic, several recursive loops between the design and analysis tasks are generally required. Given the number of research projects being conducted internationally on CAD and analysis integration, before going any further, we need to clearly define our position in relation to this research field.

2. Positioning of the approach

Given the general organisation of CAD and analysis tasks (Fig. 1), the overall goal of integrating CAD and analysis processes can be achieved in three ways:

1. Automate the conversion from a design model to an analysis model in a way that is compatible with available analysis tools. This approach is centred on the integration of evaluation tasks and tools (Cuillere, 1999; Sheffer, 1997).
2. Control the inaccuracies of the analysis process and reduce the sources of error in the analysis model. This approach can complement the integration of both dimensioning (Kurowski, 1995) and evaluation (Vignjevic et al., 1998) tasks.
3. Formalize systematic analysis procedures, which can either be applied repeatedly in the same

Table 1. Design—analysis approaches

Approach	*Advantages*	*Drawbacks and limitations*
1	– Occults secondary shapes	– Does not consider technological data
	– Provides multiple viewpoints of the simplified geometry	– Provides a one-way link between design and analysis
		– Is not applicable in early design stages (only at the evalua-tion stage)
2	– Controls errors	– Provides only error-based evaluations of the analysis
		– Does not consider analysis in the early design stages
3	– Takes technological data into consideration	– Has no genericness or general template for the analysis processes
	– Assists in the preparation of the analysis	– Requires that users be experts in the analysis domain.
	– Records sequences of the analysis	– Models only partial steps of the analysis process

context, or parameterized to fit a variety of similar, but different contexts. This approach concerns both dimensioning (Troussier, 1999) and evaluation tasks, intrinsically (Fischer, 2000).

Aifaoui (2003) provides a detailed discussion of the principles of these three approaches to CAD/analysis integration. Table 1 highlights the advantages of each approach as well as its drawbacks and limitations.

Our approach falls into the third category of this classification; it aims to allow effective interoperability between design and analysis processes, in order to ease and accelerate the creation of individual analysis loops, while also allowing analysis sequences to be reused. Our approach also requires all phases of the analysis modelling process to be taken into consideration—from the design problem to be analysed (start of the loop) to the interpretation of the results (end of the loop). Thus, our goal is to define a generic model permitting a bi-directional relationship between multi-domain product design models and a variety of mechanical analysis models. Our preference for generic-ness required an original research methodology, which is presented in the following section.

3. Research methodology

In order to make our methodology generally applicable, it was necessary to analyse and compare several different real cases of design-analysis problems, involving representative classes of the analysis processes used in the field of "solid mechanics". With this in mind, we conducted an experimental study of real design cases involving mechanical products, in which the chronological and tactical organisation of the design and analysis tasks and their respective usefulness were identified. As a refinement of this study, each analysis task was individually analysed from a functional point of view, using a common formalism: IDEF0.

Figure 2 shows the general IDEF0 model of an analysis task. In this IDEFO model, an analysis task is represented by a box, which receives input (product data and assumptions: mechanical model), produces output (analysis results from a given viewpoint), respects constraints (observation model) and requires support (simulation model).

4. Synthesis of case studies

Four very different products (complete design case studies) were considered, and identical analyses of their respective design processes were conducted. A matrix-based comparison of each analysis task showed that, regardless of the phase in the design process or the kind of analysis task (dimensioning or evaluation), three different models could be defined and subsequently validated using a LIFO policy. Our search for generic-ness was satisfied because this study indicated the existence of a

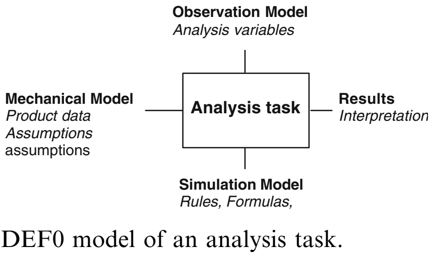


Fig. 2. IDEF0 model of an analysis task.

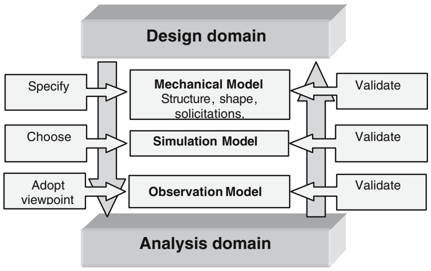


Fig. 3. Generalization of design and analysis process.

high-level recursive process, characteristic of the loop between a design problem and the response generated by task analysis (Fig. 3).

This loop can be seen as an implementation of a V-cycle (Yannou, 2002), which encompasses three models:

1. *A Mechanical Model (MM)* is directly connected to the design product model. Based on mechanical assumptions, it represents the structure, the simplified shape and the behaviour of each element of the mechanical structure and the known distribution of solicitations.
2. *A Simulation Model (SM)* is characterised by the rules, formulas, and procedures likely to produce an evaluation of the product's mechanical behaviours, as characterised by the previously constructed MM.
3. *An Observation Model (OM)* represents a set of relevant observation variables allowing the product's behaviour to be assessed. These variables correspond to specific viewpoints concerning the product's mechanical behaviour. They are derived from the implementation of selected SM.

This representation seems sufficiently generic to fit a variety of design contexts. It allows the three models (MM, SM and OM) to be configured differently, according to the problem. Despite our hypothesis that this framework would provide the most general model of every possible closed loop existing between design and analysis, it was nonetheless necessary to further refine the model to allow specific classes of problems to be addressed in the most conventional way. This refinement or specialization produced an ontology consisting of generic concepts and models. The notion of "feature", extensively used in the scope of CAE applications with Information Technology (IT) since the 1980s, is exemplary for the management of such ontology, and has been considered as a good means to aggregate the generic models derived from our experimental study.

5. The concept of Analysis Features

Initially, the "feature" concept was used for the enhancement of shape semantics, particularly when correlating product geometry to the product's manufacturing significance (Joshi, 1991). Later on, different CAE applications of the feature concept were developed, including functional features (Zhang, 2001), assembly features (Deneux, 1998), and meshing features (Cuillère, 1999; Razadan, 2003). Most of these applications are consistent with the generic definition suggested in Shah (1991), who defines the feature concept as an abstract entity that has several significances depending on the context. The Analysis Feature (AF) can be defined as "a parameterized generic entity characterizing a mechanical analysis class". An AF can be characterized algebraically as AF = {MM, SM, OM, *R* (MM, SM), *R* (SM, OM), *R* (OM, MM)}, a 6-tuple that involves the three data models introduced in the previous section, and the following three relationships between these models, all of which support the AF model's overall consistence:

1. The *R* (MM, SM) relationship is a *continuity relationship* that allows data to be transferred from MM to SM.
2. The *R* (SM, OM) relationship is an *observation relationship* dedicated to extracting, from a simulation, the observation variables needed to analyse a structure's behaviour, according to a specific viewpoint chosen by the designer.
3. The *R* (OM, MM) relationship is a *validation relationship* that permits the initial assumptions established in MM to be validated, according to the interpretation of the structure's behaviour.

The AF has to interact with several product-modelling domains, particularly the technological domain (in which kinematics and static effort analyses are performed) and the technical domain (in which experts select standard components, and analyses of dynamic efforts and resistance to stress are performed). Every time an analysis task is implemented, the following generic process, shown in Fig. 4, is employed. First, an MM is specified according to certain assumptions. Then, an appropriate SM is selected for this newly constructed MM. Finally, based on the simulation results, an OM is selected that allows the mechanical behaviour of the product to be analysed. The interpretation of the OM may validate, or **in**validate, the OM itself, the SM, or even the MM.

In the following sections, detailed models of some representative analysis features, as well as the

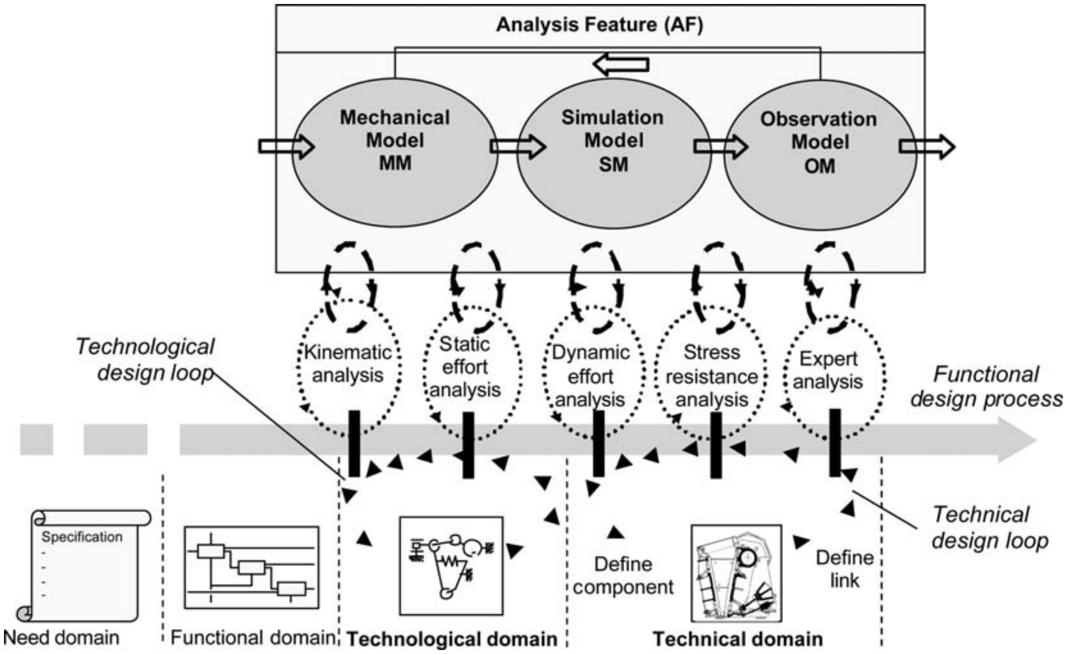


Fig. 4. Generic analysis process thru the analysis feature.

data supporting the interoperable design and analysis processes, will be provided. However, it is first necessary to detail the product model upon which the assembly feature operations will be performed.

6. Product model

The product model is actually a set of interconnected models, which characterize the different steps of the product design process, from the expressed need to its complete definition (El Mahalawi, 2003a, b). According to Jacquet (1998), there are five main product modelling domains: requirement, functional, technological, public technical (expression of technical solutions common to all design actors), and private technical (expression of technical solutions specific to an individual or to a restricted group of design actors). Our study focuses principally on the technological and public technical domains, because the corresponding product modelling entities are most affected by mechanical analysis tasks (Aifaoui, 2003). In the next two sub-sections, the entities of the technological and technical modelling domains are examined in detail. Fig. 5 illustrates the technological and technical representations of the same product.

6.1. *Entities of the technological model*

In the technological domain, the product is represented by a technological solution that is composed of technological components connected by mechanical interfaces. Such solutions can be subjected to various constraints, including space and mobility, among others. The basic concepts of the technological model include the technological component, the interface, the technological solution and the constraint.

- *Technological component*: a technological component is a non-decomposable entity depending on one technology. It has a local reference and an autonomous behaviour related to its function in the technological solution.
- *Interface*: from a mechanical point of view, an interface represents a mechanical connection between two technological components (i.e., a pivot joint). It has both a local reference and a type, and has varying degrees of freedom (rotation and translation).
- *Technological solution*: A technological solution describes a transformation of energy and/or motion. It implies an organization of technological components connected by mechanical interfaces and can be represented by a graph structure.
- *Constraint*: There are two principal types of constraints: space constraints (pertaining to the space in which the components are allowed to move), and mobility constraints (concerning the degree of freedom at the interfaces). These constraints can be either local (applied to an interface or a component)

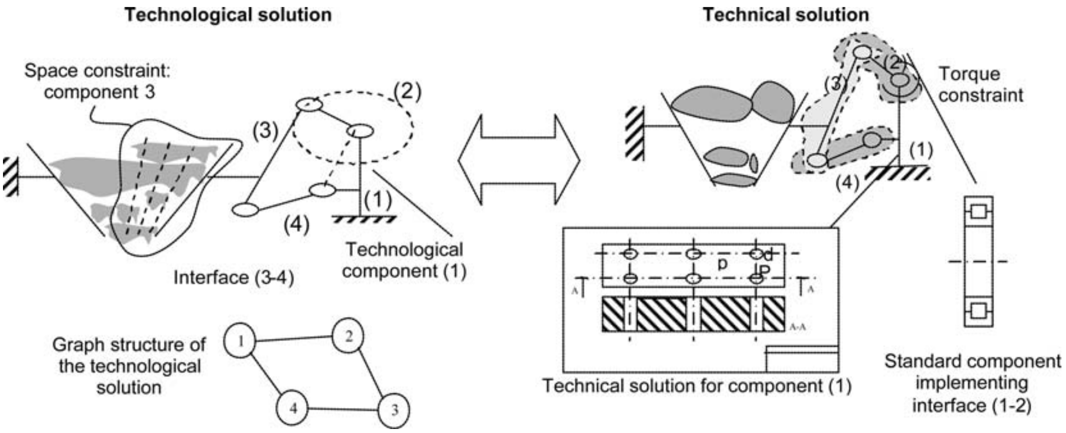


Fig. 5. Technological and technical solutions for a stone crusher.

or global (applied to several components or several interfaces).

6.2. *Entities of the public technical domain*

In the technical domain, designers concretize the technological components and the mechanical interfaces that were defined in the technological solution. They successively define the geometry, the dimensions and the materials that characterize the non-standard technical components, or they define the types and parameter values for standard components, such as gears, bearings, or fixing elements. The basic concepts of the technical model include the technical component (standard or non-standard), the technical solution that determines the organisation of the technical components, and the constraint.

- *Technical component*: a technical component is an entity composed of some identifiable material, has a geometrical envelope including functional and complementary shapes, and behaves autonomously. Standard technical components do not need to be engineered, and can be selected from a catalogue of parameterized components. These components are used in the majority of mechanical systems to construct mechanical interfaces; each one is characterized by a type and a set of functional dimensions. Non-standard technical components must be engineered specifically for the job they are meant to perform and cannot be ordered from a catalogue. Nonetheless, like standard components, they are characterised by a type and a set of functional dimensions.
- *Technical solution*: according to Jacquet (1998), a technical solution represents a set of physical solutions (that all have shapes and a material) and concretizes the technological solution by means of a particular organisation of technical- and standard- components.
- *Constraint*: constraints determine the criteria to be used for validating a technical solution. There are many types of technical constraints, including but not limited to resistance, positioning and accessibility.

Figure 5 represents both a technological solution and a technical solution for the same product (a stone crusher). Some of the constituting entities have been identified.

Our experimental study of several design cases permitted the identification of two analysis feature classes in the technological domain (a *Kinematics Feature* (KF), for motion analysis and a *Static Feature* (SF) for stress analysis at the interfaces) as well as one analysis feature class in the technical domain (a *Resistance Feature* (RF), for analysing the resistance of technical components subject to stress). These three feature classes have been completely characterized in Aifaoui (2003). In the following section, only the KF, which is representative of our approach, is described in detail.

7. Description of the "Kinematics Feature"

The KF is defined as a generic entity, which can be used by designers to study the motion of mechanical products (displacement, velocity, acceleration), in order to define or validate a specific technological solution. The following section describes and justifies the models and the coherence relations that characterize KF.

7.1. *Mechanical model of the kinematics feature*

The goal of the mechanical model (MM) is to completely or partially represent a technological solution, taking into account some mechanical assumptions about the parts' shape (beam, shell, ...) and expected behaviour (rigid, deformable, ...) and about the solicitations to be beard by these elements. These assumptions help produce a realistic MM derived from the designer's product model.

7.1.1. *Assumptions related to structure*

A technological solution structures the series of technological components and interfaces. Depending on the goal of an analysis, splitting the initial structure into sub-structures may be desirable in order to facilitate a local analysis. On the other hand, globalizing the structure (by combining several sub-structures) may provide the analysis with a wider focus. In either case, each identified (sub-) set can be described by a graph structure and examined according to a specific set of assumptions.

7.1.2. *Assumptions related to the technological components*

- *Existence*: the structure can be simplified by ignoring the existence of those technological components that are not expected to be pertinent to the planned analysis.
- *Geometry*: simplified shapes can be specified for each technological component (e.g.: straight-curve, elliptic-curve, poly-line).
- *Behaviour*: the typical behaviour of each technological component in the mechanical system must be specified as either *rigid* or *deformable*. In kinematics studies, components are generally assumed to be rigid.

7.1.3. *Assumptions related to the interfaces*

- *Mobility*: by increasing or decreasing the degree of freedom at the interfaces, the mobility of each interface in a mechanical system can be made more mobile or more rigid.
- *Friction*: each interface can be subject to friction, or not. In kinematics analyses, the interfaces are generally assumed perfect (no friction).

7.1.4. *Assumptions related to the efforts*

These assumptions concern the efforts to be beard by each element of the mechanical system. In kinematics, these efforts pertain to motions affecting the interfaces. Effort is represented by appropriate values in a kinematics tensor.

7.2. *Simulation model of the kinematics feature*

The simulation model (SM) of a KF is an MM calculation model. It reproduces the evolution laws of the variables that characterize the motion of the structure. Through our experimental study, two SMs were identified (Bacon, 2000; Decolon, 2000):

- The first SM (SM1) parses the graph structure in order to produce a list of geometric closed loops and to calculate the cyclomatic number. This number is useful for identifying independent cycles in the technological solution, which allows local behaviours to be distinguished from global behaviours. SM1 is represented by a simple equation: $\mu = N_i - N_c + 1$, where μ is the cyclomatic number, N_i is the number of interfaces, and N_c is the total number of technological components.
- The second SM (SM2) is based on the concept of a vector graph. It is used to simulate the kinematics behaviour (i.e.: trajectory, velocity and acceleration) of a rigid technological component in a closed loop, assuming knowledge of the behaviour of each component in that loop. The position of component V_{i+1} (local reference R_{i+1}) relative to component V_i (local reference R_i) is expressed by:

  $$\vec{V}_i\Big|_{R_i} = M_{i,i+1} \cdot \vec{V}_{i+1}\Big|_{R_{i+1}}$$

  where $\left[M_{i,i+1}\right] = \begin{vmatrix} R & U \\ 0 & 1 \end{vmatrix}$ is the homogeneous transformation matrix from reference R_{i+1} to reference R_i due to translation and rotation.

7.3. *Observation model of the kinematics feature*

The Observation Model (OM) is a set of observation variables concerning the mechanical behaviour of a product. These observation variables are possible outputs of the SM described above. Table 2 presents a candidate OM based on the information collected during coming our experimental study.

7.4. *The relationships between the MM, SM and OM of the kinematics feature*

An analysis feature integrates three models and three relationships. Figure 6 depicts the possible list of associations between selected models of the MM, SM and OM as related to the kinematics feature, based on the limited set of models collected during our experimental study.

In Fig. 6, an existing link between two models (or a "1" in the correspondence table) means that the two models are compatible, i.e., the rightmost one can be constructed using the leftmost one. For

Table 2. Observation model of the kinematics feature

OM	*Definition*	*Representation model*
OM1 Cyclomatic number	Dimension of the cycle base in a structure graph. This number is directly determined from the number of nodes and arcs in the graph.	Scalar: $\mu = N_l - N_c + 1$
OM2 Displacement (linear, circular…)	Set of positions occupied by point A_i of component C_i in a local reference R_{ci} between two time limits t_0 and t_1	Table of values evolution law (displacement $= f$ (time))
OM3 Velocity (linear, circular)	Quantifies the variation of position, and is derived from position vector $OA_i(t)$ in a local reference R_{ci}., where O is the origin.	Table of values evolution law (velocity $= g$ (time))
OM4 Acceleration (linear, circular)	Quantifies the variation of velocity, and is derived from the velocity vector of the same point of the part in the same local reference R_{ci}.	Table of values evolution law (acceleration $= h$ (time))

example, relationship R (SM2, OM3) means that the velocity of a component can be computed from a valid vector graph.

The purpose of the validation relationship is to verify that the assumptions formulated in the MM are consistent with the observation variables produced by the SM. Depending on the application domain, this relationship may be characterised in many ways: for example, by an order of magnitude, a definition domain or a tolerance zone, among others. This ability allows the simulation output to remain consistent with the kind of problem under consideration (microsystem, agricultural equipment, shipbuilding equipment, etc.). This validation relation is intended to be used to facilitate the designers' interpretation, after the analysis has been performed and the results obtained. Here, all the values of the relations between OM and MM have arbitrarily been set to "1", which means that no particular constraint has been defined for the kinematics feature class.

The two other feature classes touched on briefly in this paper—the static feature and the resistance feature—can be characterised similarly. Due to the variety of models in each feature class, many analysis features can be constructed in each class in the same way. The following section describes how to organise these numerous features into a catalogue.

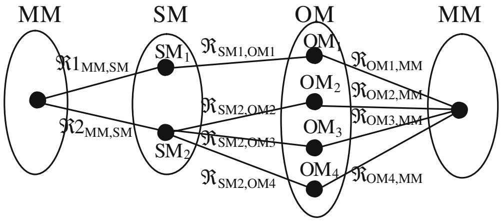
8. Catalogue of features

Each AF describes a particular process starting with the formalisation of a design problem, involving an observation variable calculated via a mechanical analysis, and ending with the interpretation of that variable within the design context. The purpose of a catalogue is to organize all the AF. Depending on the specificity of the problem encountered, such an organization can help limit the number of AF sets that must be examined by a designer during the design phase. Such a catalogue can subsequently be organized in terms of *analysis domain*, *modelling domain* and *analysis type*, for example.

Thanks to the catalogue, features can be modelled a priori using a top down approach (MM first, the SM, then OM), defining the common characteristics of feature classes first, before to particularize specific classes corresponding to specific analysis processes.

Figure 7 presents our general catalogue. One specific analysis domain, "solid mechanics", is presented in detail. It includes sections for two modelling domains, respectively technical- and technological-, and offers the possibility for different analysis types, depending on the modelling domain (*kinematics* or *static* in the technological domain, or *resistance* in the technical domain). A tree representing a non-exhaustive list of particular models at the MM, SM and OM levels is also included, as well as several kinematics features, identified separately at the bottom of the figure.

These particular features were identified in the experimental study, and are represented by a constructive tree corresponding to the modelling choices usually adopted by designers. Designer specifications are built by refining assumptions and modelling choices related to the structure, technological components, interfaces, solicitation, and the simulated and observed behaviour. Section 9 addresses the issue of implementation and the corresponding specifications.



Association MM, SM

	SM_1	SM_2
MM	1	1

Association SM, OM

	OM_1	OM_2	OM_3	OM_4
SM_1	1	0	0	0
SM_2	0	1	1	1

Association OM, MM

	MM
OM_1	1
OM_2	1
OM_3	1
OM_4	1

Fig. 6. Simple relationships between models in the KF.

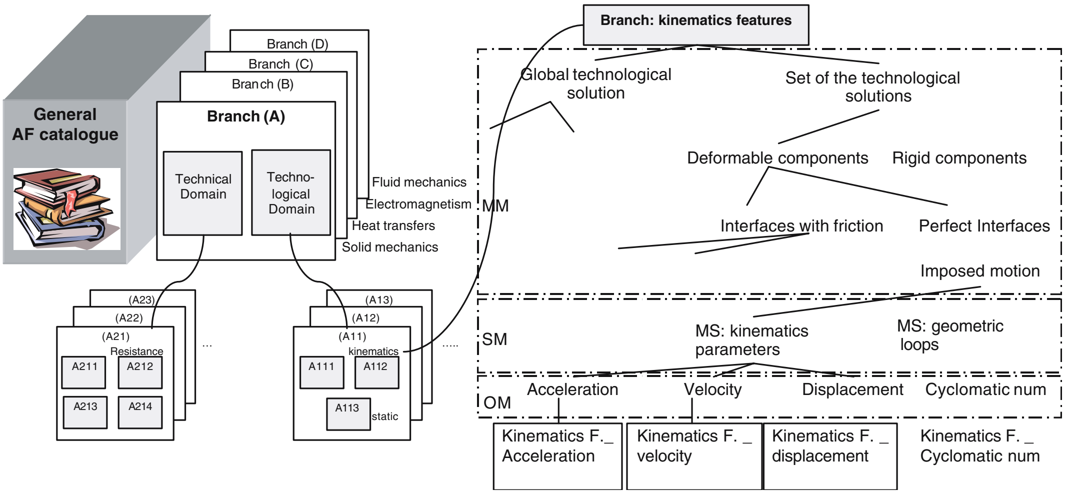


Fig. 7. Feature catalogue.

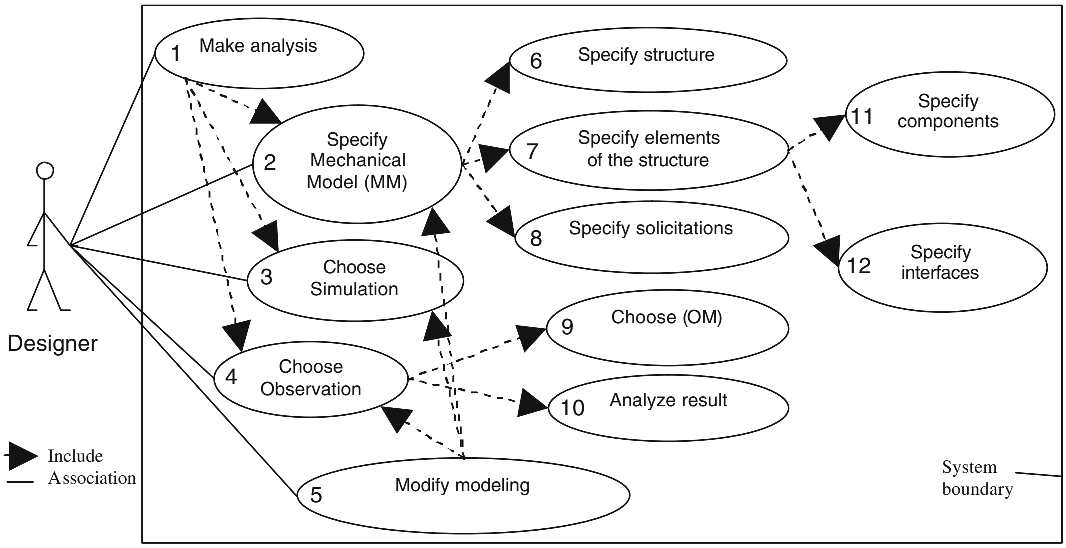


Fig. 8. User-case diagram of the analysis feature.

9. Implementation issue

In order to implement the proposed approach using information technology, it is necessary to further formalize the concept of assembly feature. For this purpose, the Unified Modelling Language (UML) formalism has been used, because it unites most of the object formalisms that have emerged in recent years. An UML class diagram provides a static view of the concept to be represented. This diagram includes attributes, relations and operations, which use the available class methods to perform automatic tasks, in particular analysis tasks.

9.1. *Class diagram*

In the catalogue diagram presented in Fig. 7, the AF class for the domain of solid mechanics is presented. This class is composed of three sub-classes. Each sub-class represents a data model (MM, SM, OM), the union of which is intended to support the analysis task. All the features related to the 3 identified analysis feature classes (kinematics, static and resistance) inherit information about structure, attributes and methods from the "solid mechanics" class.

A static view of the AF is not sufficient for defining the processes by which the features can be dynamically exploited, or to bridge the gap between design and analysis. For this reason, a user-case diagram is presented in the following sub-section to describe the catalogue's dynamic aspects. The sequences diagram in section 10 illustrates a detailed scenario.

9.2. *User-case diagram*

A user-case diagram in Fig. 8 describes the processes employed by the end-user of the AF (the designer) to perform kinematics, static or resistance analysis tasks. The set of actions described in this diagram form a typical analysis loop and are performed conjointly by the designer and the information system. The interpretation is quite self-explanatory. The "make analysis" action comprises three sub-actions: "specify MM", "specify SM" and "specify OM".

The complete validation of our approach would require actually implementing the proposed models in order to prove their ability to provide support for specific analysis loops in variable contexts. Therefore, validation requires both an appropriate scenario based on the proposed model and the coding of the corresponding procedures. The coding is presently still in progress, but the following section depicts the main steps of the scenario, which is the most important validation requirement from a scientific point of view.

10. Validation

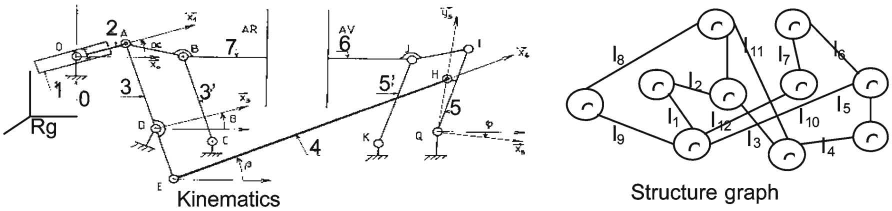
The goal of this section is to confirm that the analysis feature concept can allow the designer implement a variety of mechanical analysis tasks in a coherent way that is interoperable with the design process (i.e., the product model definition process). The AF catalogue is used here to support the design of a concrete component that is part of a mould closure system (Fig. 12). This example is representative of a significant number of mechanical systems and uses a variety of analysis tasks (kinematics, static, dimensioning and evaluation).

The overall functional design process of the mould closure system includes the following activities: first, during the technological design phase, the designer imagines and defines a possible technological model (Fig. 9). Then, this potential solution is evaluated. It is not enough that the mould closes; the closure system must also ensure that this action is rapid and that the mould remains rigidly closed, both while the material is being injected, and after.

In order to verify that the solution complies with the speed requirement, the closure velocity must be calculated, and then the time needed to perform a cycle must be evaluated. When entering the solid mechanics catalogue, the designer looks for information that will allow the cycle duration to be estimated. Such information can be found in a velocity study, which appeals for a feature belonging to the kinematics class. Figure 10 schematically represents the connection between the design process (which defines and updates the product model) and the analysis process (during which the catalogue is examined for an adequate analysis feature), showing how these processes are able to interoperate.

Figure 11 illustrates the choices made by a designer working to identify an appropriate analysis feature (velocity) for calculating the closure speed. First, an MM based on the design context is specified. Keeping in mind the design environment, the designer selects the structure of the closure system, which is explicitly defined in the technological solution. Then, he/she specifies the options pertaining to the assumptions about the components and interfaces which constitute the system. Then the known efforts—a motion type imposed by the alimentation jack, for instance—must be specified. Based on

Technological solution: « closure system»



Kinematics

Structure graph

- Ident. STO_1301
- Global reference: Rg
- Geometric representation:
- Components: {(C0: Rc0: base); (C1: Rc1: jack); (C2: Rc2, arm 2); (C3: Rc3, arm 3), (C3': Rc3': arm 3'); (C4: Rc4, arm 4); (C5: Rc5: arm 5); (C5': Rc5': arm 5'); (C6: Rc6: half mould); (C7: Rc7: half mould)}.
- Interfaces: {(I1: pivot, Ri1, Mobility: α); (I2: axial joint, Ri2, Mobility: β, y2); (I3: pivot, Ri3, Mobility: δ); (I4: pivot, Ri4, Mobility: χ); (I5: pivot, Ri5, Mobility: ε); (I6: pivot, Ri7, Mobility: η); (I8: pivot, Ri8, Mobility: κ); (I9: pivot, Ri9, Mobility: λ); (I10: pivot, Ri10, Mobility: μ); (I11: pivot, Ri11, Mobility: ν); (I12: pivot, Ri12, Mobility: θ)}
- Constraints:

Fig. 9. Technological model of a possible closure system.

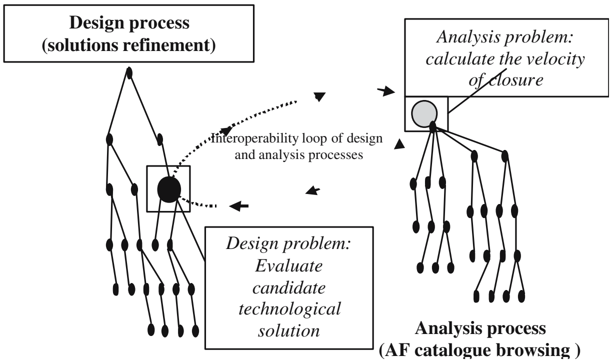


Fig. 10. Interoperability of design and analysis processes.

the MM, the designer defines an SM (analysis of the kinematics parameter procedure) and selects the adequate observation variable (velocity) to evaluate the kinematics behaviour of the solution.

Figure 12 represents the (UML) sequences diagram of the choices made. The analysis produces the OM. Interpretation of the OM results (step 3) shows that the mould closes in 0.4 s. This is satisfactory from a mechanical point of view because the OM, the SM and the MM are validated, but not from a design point of view. From the design perspective, 0.4 s is insufficient given the expected production rate.

Given the sequence presented above, the candidate technological solution cannot be validated by the analysis loop and must be reworked by the designer. Figures 10 and 11 represent only the topology of the analysis feature tree browsed by the designer and the sequence of actions performed to implement a feature object. These figures both provide a map of the design-analysis environment and trace a particular path followed by the designer. However, the designer's perception of the path taken is slightly different.

Figure 13 shows a possible user interface that would allow the selected analysis feature to be instantiated. In the same figure, the correspondence between the information manipulated by the designer, and the underlying product model and analysis catalogue are highlighted.

In order to reduce the mould's unit closure time, the designer must modify the kinematics configuration of the solution. The disposition of the power jack is modified, reducing the amplitude of the closure path by changing the alpha orientation of the piston initiating the closure effort from 0.266 to 0 rad. This preserves the architecture of the previous technological solution, while altering a single parameter value. Thus, the problem to be analysed is the same, as is the pointer marking the product model to be examined and so, the same analysis feature can be re-used.

The MM is updated, taking into account the new alpha value (Fig. 14). Possessing the path of the previous analysis allows the designer to reuse the same SM and OM. This new solution produces a new closure time of $t = 0.125$ s, which is satisfactory from both a mechanical point of view and a design point of view.

The ease with which an existing analysis feature can be updated is likely to significantly reduce the time and effort needed to implement a complete design analysis loops.

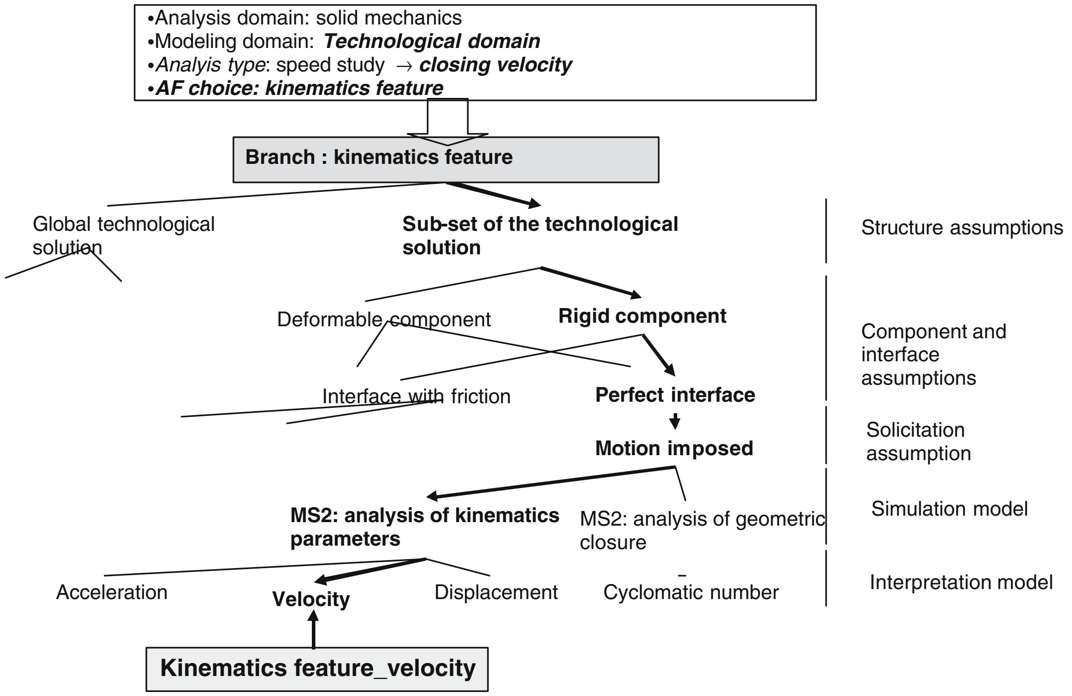


Fig. 11. Gradual definition of an analysis feature.

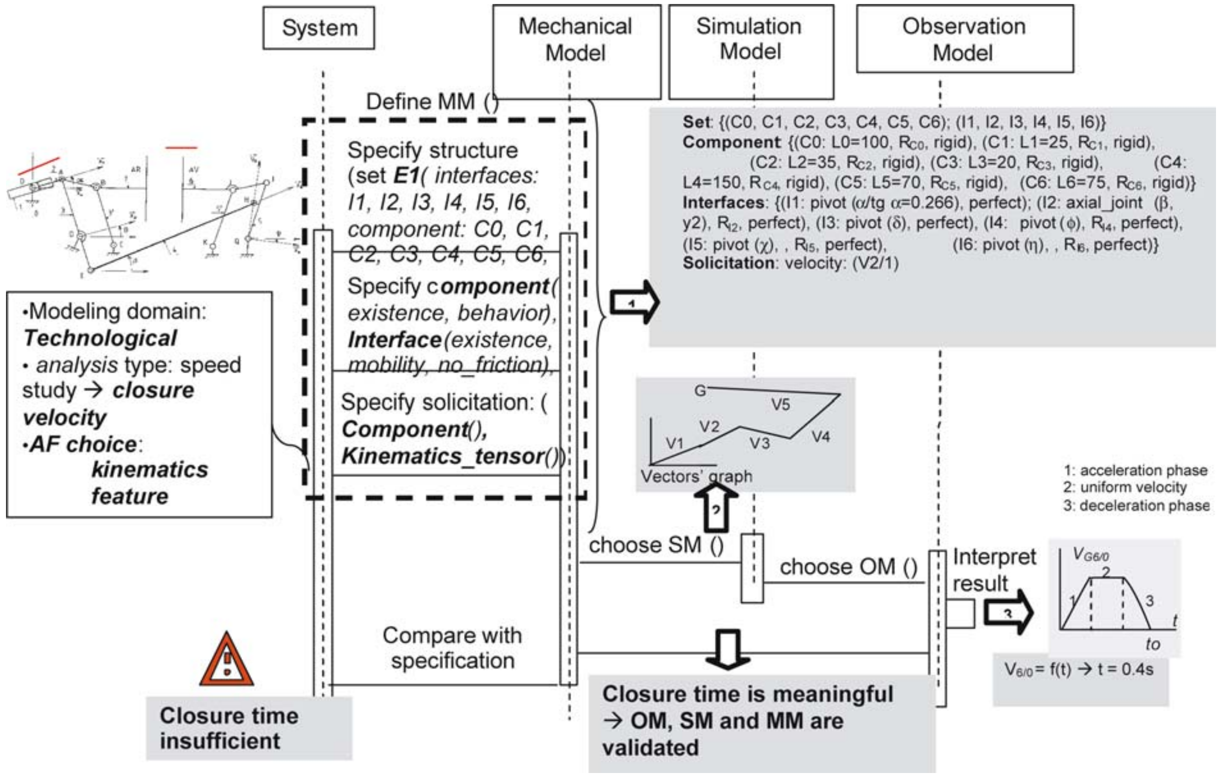
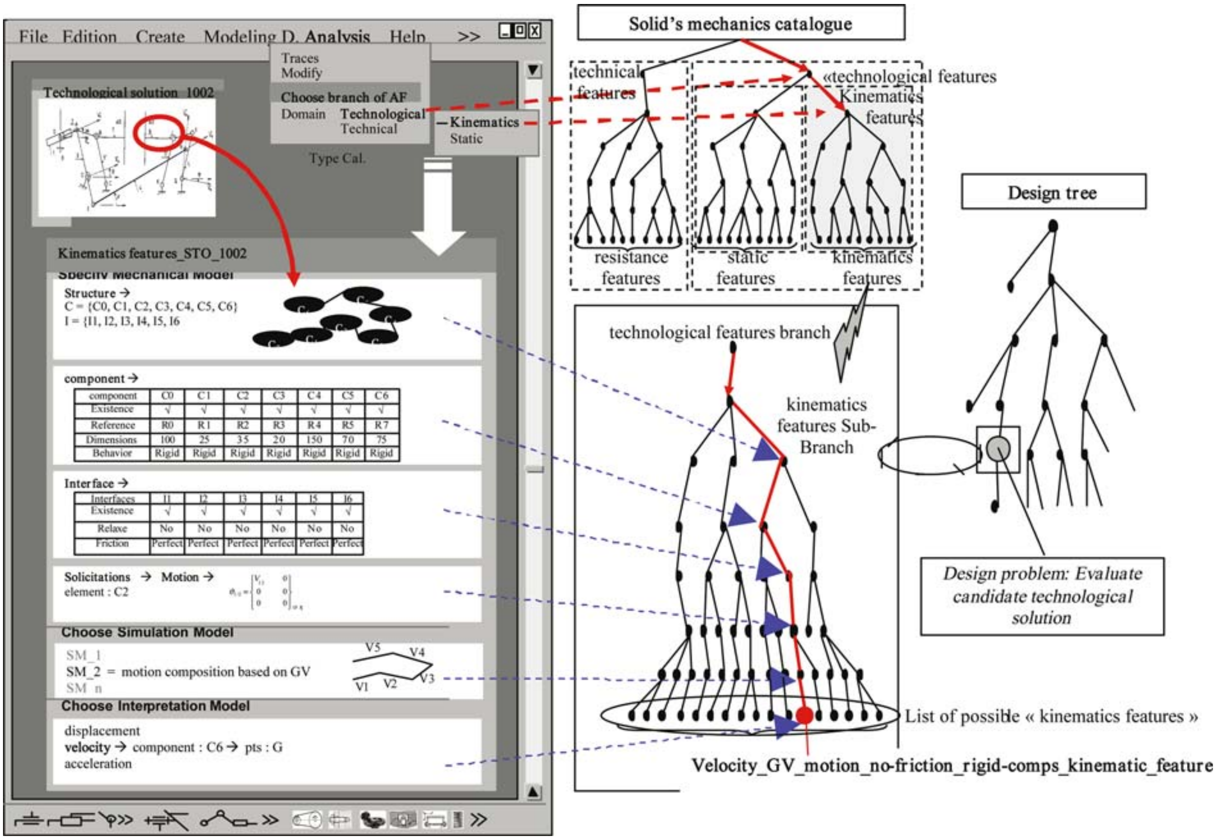


Fig. 12. Sequences diagram associated with the AF.



Kinematics features_STO_1002

Specify Mechanical Model

Structure →
C = {C0, C1, C2, C3, C4, C5, C6}
I = {I1, I2, I3, I4, I5, I6

component →

component	C0	C1	C2	C3	C4	C5	C6
Existence	√	√	√	√	√	√	√
Reference	R0	R1	R2	R3	R4	R5	R7
Dimensions	100	25	35	20	150	70	75
Behavior	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid

Interface →

Interfaces	I1	I2	I3	I4	I5	I6
Existence	√	√	√	√	√	√
Relaxe	No	No	No	No	No	No
Friction	Perfect	Perfect	Perfect	Perfect	Perfect	Perfect

Solicitations → Motion →
element : C2

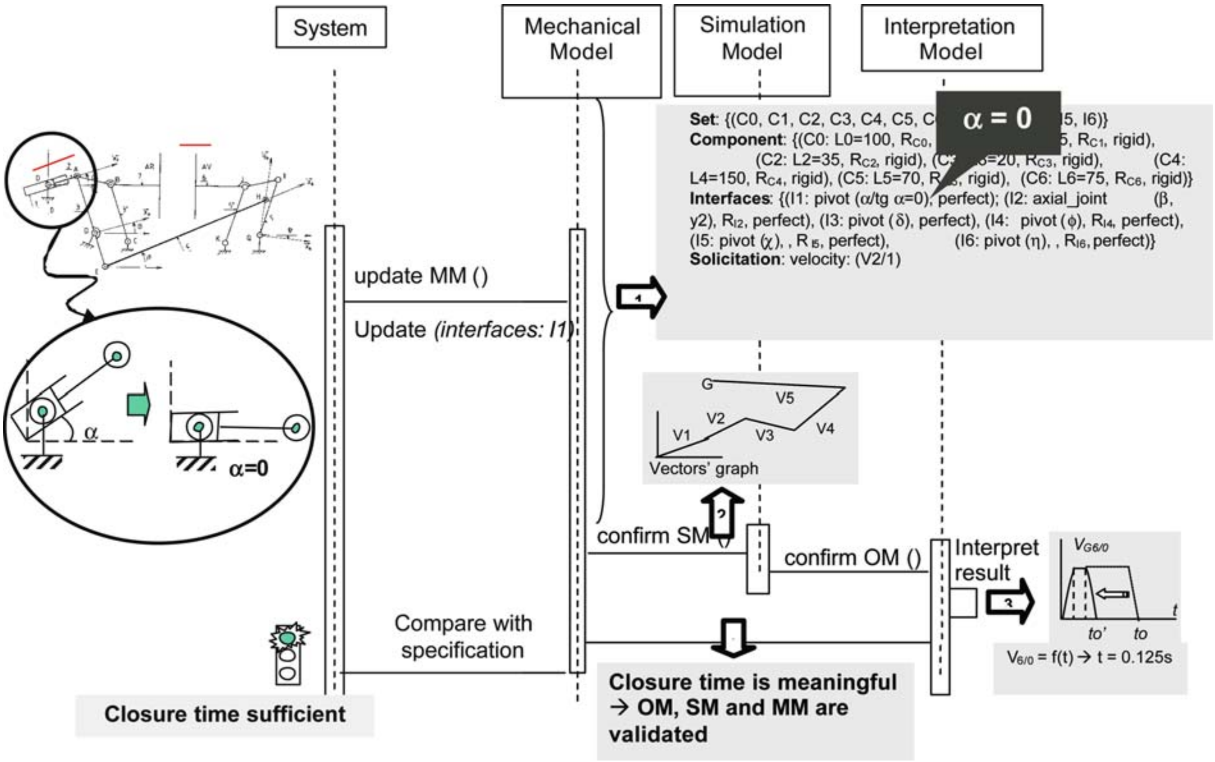
Choose Simulation Model

SM_1
SM_2 = motion composition based on GV
SM_n

Choose Interpretation Model

displacement
velocity → component : C6 → pts : G
acceleration

Fig. 13. Possible user interface for AF definition.



Set: {(C0, C1, C2, C3, C4, C5, C … I5, I6)}
Component: {(C0: L0=100, R_{C0}, … 5, R_{C1}, rigid), (C2: L2=35, R_{C2}, rigid), (C… =20, R_{C3}, rigid), (C4: L4=150, R_{C4}, rigid), (C5: L5=70, R…, rigid), (C6: L6=75, R_{C6}, rigid)}
Interfaces: {(I1: pivot (α/tg α=0), perfect); (I2: axial_joint (β, y2), R_{I2}, perfect), (I3: pivot (δ), perfect), (I4: pivot (ϕ), R_{I4}, perfect), (I5: pivot (χ), , R_{I5}, perfect), (I6: pivot (η), , R_{I6}, perfect)}
Solicitation: velocity: (V2/1)

Fig. 14. Sequences diagram of the AF update.

11. Conclusion

This paper introduces a new method improving the interoperability of the parallel processes of design and analysis. This method is based on an original concept of analysis features, inspired by Shah's definition (Shah, 1991). The application of the "feature" concept to the integration of CAD and analysis is rarely encountered in the literature (Cuilliere, 1999). But in this domain, the application of the feature concept to the modelling of generic- analysis processes, while the general approach consists in the modelling of generic-product characteristics, is totally novel, as far as the authors know. In this paper, the concept of feature is not intended to enhance the meaning of the product model from the point of view of mechanical analysis. But it is intended to support the interactive definition of analysis loops onto the overall design process, and to improve the re-usability of these loops. The concept has been illustrated here with kinematics features, but other feature types can also be considered in the domain of solid mechanics. The characteristics that analysis features share with other kinds of features include *generic-ness*, which essentially means a common model for all feature classes; *modularity*, in which a particular feature is simply a particular aggregation of the static and dynamic features inherited from superior classes; and the *ability to react* to changes in the environment.

The concept of analysis feature can be formally defined as 6-tuple involving 3-data models and 3-coherence relations. This formalization stems from an experimental study of mechanical design cases, involving several typical dimensioning and evaluation problems in static, kinematics and dynamics. Based on this experimental study, the structure and initial contents of a features catalogue was defined.

The proposed approach permits the resolution of several analysis problems encountered in the field of solid mechanics, usually in the early design phases of mechanical system design. Our approach can provide traceability to the analysis loops, allowing the re-use of existing analyses, and thus reducing the time and effort required to perform this trial and error process.

Although there is currently no working prototype, the question of implementation has been considered. The specification of a feature-based interactive design-and-analysis system has been prepared using the UML formalism. Thus, the catalogue-class diagram, the principal user-cases, and the feature selection and definition processes have been considered and detailed (Aifaoui, 2003). The product modelling environment in which our propositions are based was completely developed in the Opencascade® environment, following the specifications of (Benamara, 1998). This is the first step toward the effective implementation of this approach.

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