USE-DRIVEN PRODUCT CONCEPTUALIZATION BASED ON NUCLEUS MODELING AND SIMULATION WITH SCENARIOS

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1 KEYWORDS

conceptual product design, use process

2 ABSTRACT

Conventionally, simulation of product behaviour is employed as a pre-realization type of assessment at the end of the design process, making only late feedback for improvement possible. Enabling the start of optimization in the conceptualization is expected to have significant influence on design efficiency. However, the available information at that stage is uncertain, incomplete, multifold and imprecise, which calls for new simulation techniques. This paper proposes nucleus-based modelling and simulation as a solution. A nucleus is a modelling entity to capture the relationships between the lowest level metric elements of the product and to represent the physical effects governing the behaviour of the product. Tolerating uncertainty, incompleteness, modality and imprecision, a nucleus-based model is able to provide an integral model of the actors of the use process. Simulations are controlled by so-called scenarios that arrange a logical structure of feasible situations for the integral model. The paper describes the content of the nucleus-based integral model and presents an application case study to illustrate the potentials of this new approach.

3 INTRODUCTION

In the design process, simulations facilitate the anticipation of what happens with products during their life cycle, a crucial part of which is the use stage. However, typically, simulations do not offer a complete picture of the mutual interaction between a product, its user or users and its environment during use. Predicting operation from this broader perspective is considered to be beneficial especially in conceptual design. Regarding anticipation of use, concrete problems with the available geometry-oriented modelling environments and simulation tools boil down to the problem that current simulation packages cannot cope with interventions that naturally occur in use processes.

Furthermore, the pre-realization type of assessment during detail design for which simulation methods and techniques are typically intended, assumes that the main design process has been completed and the product model is available in testable form. The results of the simulation are used to correct the model and to provide confirmative feedback to the designers at a late stage of product design, when the changes are costly and time-consuming. The major problem with the approach is the late feedback and the lack of in-process optimization of the functionality. Current efforts are towards starting the optimization of a product in the conceptualization, which is the design phase that has the most significant influence on the incurred costs and the value of the product. The information in the stage of conceptualization is however uncertain, incomplete, multifold and imprecise, which calls for new techniques in simulation of the behaviour.

To consider aspects such as product use in the conceptualization, new modelling and simulation approaches are needed. This paper proposes nucleus-based modelling and simulation as a solution. A nucleus is a modelling entity to capture the relationships between the lowest level metric elements of the product and to represent the physical effects that are governing the observable behaviour of the product. Tolerating uncertainty, incompleteness, modality and imprecision, a nucleus-based model is able to provide an integral model of the actors of the use process, that of the user *(U)*, the product *(P)* and the environment *(E)*. The time history of the relationships implies elementary processes that are the basis of behavioural simulation. The simulation processes are controlled by so-called scenarios that prescribe typical use situations and arrange a logical structure of feasible situations for all elements included in the integral model. The paper describes the content of the nucleus-based integral model. We present the methodology that enables us to generate resource-integrated models and scenarios to deal with the use of products, and provide a template to specify the content of the models as well as a procedure to apply the methodology in conceptual design. The hypothesis is that by providing a homogenous representation for U, P and E, a comprehensive model can be developed that allows not only modelling and simulating known use processes in various situations, but also predicting use processes in ad-hoc situations. Based on the investigation of the models, in particular of the forecasted behaviour, designers can improve products for use by devising the most appropriate design concepts and configurations. The validity of this hypothesis has been explored by performing tabletop research. A use-oriented conceptual model has

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been realized in a commercially available system as a test-bed.

4 STATE OF THE ART IN USE FORECASTING AND SIMULATION

Earlier, the authors presented a survey on the consideration of the use of products in computer-aided conceptual design (Van der Vegte and Horváth 2002). Highlighting the most important definitions and presenting the findings about the state of the art, this survey can provide the reader with additional relevant facts. Below we restrict ourselves to the core problems of modelling and simulating use processes in the course of product conceptualization and early simulation. The use of products can be defined as ‘employment or application to a purpose’ or more specifically ‘direct handling of technical aids to achieve a particular goal’, implying for the product working in service of, and having contact with the human body and the brain. Use is an interaction between the three actors, *U, P* and *E*, involving mutual exchange of matter, energy and information.

In approaches for simulating behaviour of the three actors in the use process, we can distinguish artefact simulation techniques for the behaviour of products and environments and human simulation techniques for the behaviour of users. In both areas we distinguish three categories: simulations based on equations or purely mathematical models, simulations based on discretized system representations and simulations based on artificial-intelligence (AI) techniques.

4.1 Artefact-behaviour simulation: simulating behaviour of the product and the environment

In artefact-analysis models, the conventional approach to simulation is to devise a set of symbolic equations specifying a particular situation or a class of situations (Bryant et al. 2001). By solving the equations analytically in the time domain, the course of a process can be predicted. One frequent reason for unavailability of analytical solutions is complexity. Products, environments, and product-environment systems are usually complex and therefore difficult to simulate, even after idealization. A mathematical consequence of increasing complexity is that nonlinearities in the system behaviour can no longer be neglected. Research efforts are increasingly directed towards enhanced simulation techniques that can deal with non-linearity. With the increasing power of computers, *numerical methods* have gained popularity. The most straightforward numerical methods are typically purely mathematical recipes for solving particular types of ‘difficult’ equations (Riley et al. 1997).

Other numerical techniques do not predict the course of a process by solving equations for an idealized system, but based on a *discretized* representation of the system. Discretization takes place by building up artefacts from stereotypical solution elements. The elements carry knowledge about a certain behaviour. Usually, the behaviour knowledge is a linearized simplification of the actual physical behaviour. Some widely applied simulation techniques based on discretization are bond graphs (Redfield & Krishnan 1992; Finger et al. 2001; Zeid & Overholt 1995), finite-element modelling (FEM) (Zienkiewicz & Taylor 2000; Bailey et al. 1998) and mass-spring modelling (Terzopoulos et al. 1987; Baraff & Witkin 1998; Jansson & Vergeest 2000).

The third approach to artefact-behaviour simulation lies in the application of AI techniques. Unlike the numerical techniques, most AI-based techniques are not yet widely applied in design. Part of the behaviour is controlled by rules stored in knowledge bases, making *qualitative* simulations possible as well. A well-known example is the application of qualitative reasoning (Forbus 1984). Other common AI concepts applied in artefact-behaviour modelling are agents (Mah et al. 1994), neural networks (Masini et al. 1999) and ontologies (Horváth et al. 1998).

4.2 Human-behaviour simulation

Simulation techniques for human behaviour can be subdivided into the same categories that we identified in artefact simulation: (1) simulations based on equations or purely mathematical models, which are usually case-specific (Therrien & Bourassa, 1982); (2) simulations based on discretized system representations, such as FEM models (Koch et al. 1998), bond graph models (Pop et al. 1999) and mass-spring models (Porcher Nedel & Thalmann 2000) and (3) simulations based on AI techniques, such as neural networks (Martens 1998) and agents (Badler et al., 1993). We found that the simulation approaches could best be characterized by the aspects of human behaviour they cover, subdividing human acting into the behaviour types *perceptual, cognitive, control, active physical* and *passive physical* (note: *passive behaviour* means that a body is deformed or moved by external impact only; *active behaviour* means that a body is deformed or moved by internal muscular activity). The result of this characterization is shown in Table 1.

Table 1: Coverage of Human-Behaviour Types by Simulation Approaches from Investigated Literature

		perceptual behaviour	cognitive behaviour	control behaviour	active physical behaviour	passive physical behaviour
Equation-based simulations		X		X	X	X
Simulations based on structural / numerical models	bond graphs			X	X	
	finite-element models				X	X
	mass-spring models				X	
AI-based simulations	neural network-based models		X	X	X	
	agent-based models	X	X	X	X	

4.3 Applicability in use-process prediction

The review of actor-simulating techniques made it clear that a broad range of behaviours determining the interaction between the user, the product and the environment is covered by existing simulations, but there is no technique that covers all relevant aspects. Thus, a valid question would be, if integrating all those simulations into an overall use-process simulation technique can be the most auspicious way to realize use-process forecasting. After all, there are obvious tendencies towards more integrated forms of simulation already, for instance multiphysics (Mahoney 2000). However, if we want to integrate simulation techniques, we need to take care of the models first, because all simulations are imposed on models of the actors, and the problem with these models is that they typically focus on a specific aspect. From section 5, this issue will be investigated more specifically.

Apart from the modelling issue the drawbacks of commonly used simulation techniques are: (1) the simulations are orientated towards the behaviour of artefacts (*P* and *E*), but if *P* and *E* appear together with *U*, they typically only include passive behaviour of *U*; (2) unlike phenomena describing the pure physical behaviour of *P* and *E*, phenomena that rule the active behaviour of *U* cannot straightforwardly be embedded in geometry; (3) associating a product *P* with different *U*s and different *E*s is not supported; (4) simulations tend to be restricted to behaviour that is completely determined by one initial state. The bottle-neck appears to be with simulating humans. Where simulation techniques represent active human behaviour, they do so through deterministic algorithms. In reality, the active behaviour of humans is controlled by mental processes, which make it non-deterministic.

A related weakness of simulation techniques is that they cannot handle multiple scenarios that have to be dealt with because of (1) the possible multiple outcomes of non-deterministic human behaviour, (2) multiple users, and (3) multiple environments. It does not seem feasible to consider all the possibilities but for many products, a considerable amount of such knowledge can be gathered, for instance, from historical data (from existing products). In (Van der Vegte et al. 2002), we presented an approach to handle this knowledge and make it available in conceptual design. From section 8, we elaborate on handling scenarios and the subsequent application of simulation techniques to investigate the more or less deterministic behaviour.

5 MODELLING ISSUES

The expansion of CAD/E systems to conceptual design introduces problems in terms of the modelling entities. When we take into account the modelling approaches that follow the mental processes and the thinking of designers, and, in addition, reflect the way the majority of designers would prefer to enjoy computer support, the current solutions are far from optimal. Just consider, whatever it involves, computer support of conceptual design. The overwhelming majority of the currently used systems have been developed to support detailed design and downstream application oriented modelling with geometry in the centre, to enable analyses and simulations. Research systems offer specific approaches to specific problems of conceptual design based on dedicated theories, but they are typically not connected to, and difficult to integrate with, the above mentioned systems due to the high level of abstractions in the models. Although many researchers believe it is totally in line with the nature of conceptual design, other solutions can also be thought of. Actually, this is the primary objective of the nucleus-based approach presented here. With computer aided conceptual design in the centre, we sketch up a new way of thinking about modelling, which lends itself to a more evocative formation to models, following the way of thinking of designers.

The requested increase in the capabilities of CAD systems assumes ‘smarter’ modelling entities to be shared in modelling, analysis and simulation. The focus of our research into new modelling entities is on conceptual design. Conceptual design works with design concepts that are typically abstract, incomplete and vague. Detail design is for a comprehensive specification of the geometric features and mechanical attributes of the parts and the assembly. Whilst early behavioural simulations provide information about the expected behaviour mainly by qualitative reasoning, advanced behavioural simulations are to qualitatively investigate the behaviour of a product and of the components of it in both the space and time domains.

On the level of functional and methodical requirements, we envisage computer-aided conceptual design (CACD) systems to have the capabilities to handle incompleteness, vagueness and impreciseness of models and information, to be able to provide fast simulations of the physical behaviour of the product during conceptual design, involving the related humans and the environment and to support in-process physical modelling. The CACD systems fulfilling these requirements will operate as front ends of the conventional CAD/E systems, facilitating detail design and numerical analysis of parts, assembly design and behavioural simulation of products.

Application feature modelling is the current paradigm for detailed geometry, assembly and manufacturing modelling as well as for downstream activities (Noort 2002). The major shortcoming with respect to behavioural simulation is that feature technology is confined to handling permanence rather than changes. Practically each natural and artificial system is of a transitory nature that manifests in observable behaviour that is realized by the interactions of function carriers of different mechanical components. Conventional feature representations are application dependent and intend to capture morphological aspects rather than the semantics of functions and the manifestations of operation/behaviour.

Being aware of the potential of feature technology, the objective of our research has been to find possible answers to questions such as: What modelling entity concept comes in product modelling when the feature paradigm is exhausted? What information and/or knowledge have to be conveyed by these entities in order to be able to support conceptual modelling/simulation and detail modelling/simulation equally well? In the next section we propose the nucleus theory as a basis of next generation product modelling, explaining the innovative concept and showing that it results in a family of modelling entities that dramatically extends the functionality of current feature entities. The major difference relative to feature-based modelling is that the notion of geometric entities as fundamental building blocks is abandoned in favour to relations that actually govern the formation of geometry.

6 PRESENTING THE NUCLEUS AS A NEW MODELLING ENTITY

It is presumed that any new modelling entities should support feature-based design and processing, i.e., it has to support feature technology in general. In addition, the introduction of some new modelling entities should lead to knowledge-intensive conceptual models offering new functionalities for the designers to conceptualise products. We hypothesized that a new modelling entity has to focus on design concepts that are intuitively or systematically generated by the designers and to make it possible to represent their elements and entirety. It implies the need for a deeper understanding of the nature of design concepts and the possible ways of formalization without destroying creative power. It is especially important with respect to the inherent intuitiveness, incompleteness and uncertainty of design concepts and the heuristic nature of conceptualisation. Obviously, the modelling entities have to be of a very high level (or complex) to be capable to incorporate sufficient amount of knowledge for concurrent modelling of components, assemblies and systems. It amounts to saying that the current systems are somewhat limited in these capabilities.

We developed the nucleus theory as a foundational theory of a new product modelling methodology, and studied the feasibility and applicability. Below we explain the fundamental concepts and clarify the specific notions. From investigation of various engineering products we found that they all can ultimately be decomposed to a purposeful composition of physically coupled pairs. Any physically coupled pair can be abstracted as a composition of - typically two - interacting objects and multiple physical relations between the objects that may appear in various situations. Actually, this abstract construct gave the idea of the nucleus, which is understood as a generic modelling pattern that can be specialized to describe the constituents of a design concept or its entirety. From a programming point of view, the nucleus is a complex data and relation structure that covers geometric, structural, morphological, material and physical aspects. From a modelling point of view, this is the lowest level entity that carries both morphological and functional information to applications through the embedded structure of objects, relations and conditions.

7 FORMALIZATION OF THE NUCLEUS-BASED MODEL

As mentioned above, our intention has been to represent design concepts by a purposeful set and configuration of nuclei. With symbolic terms, we formalized a design concept as $DC = \{O, \phi, S, C, A, D, P\}$, where $O = \{(o_i, o_j)\}$ the set of pairs of objects, A = attributes of objects, ϕ = physical relations, P = parameters describing the relations, S = situation in space and time, D = descriptors of situation, C = constraints on attributes, parameters and descriptors. Design concepts can be decomposed but not beyond any limit. If the objects, relations and situations are missing, the abstraction becomes meaningless. Actually, this is another reason to call the $N = \{O, \phi, S\}$ triplet the nucleus of a design concept (Figure 1). A semantics driven decomposition of design concepts results in nuclei that represent ultimate constituents. Representation of a most elementary design concept requires at least one nucleus. Compound design concepts however need a purposeful composition of a finite number of nuclei. A situation arranges the objects in a set of relations, or, in other words, creates a given structure of elementary processes described by the mathematical formulas. A situated nucleus lends itself to computable behaviour, that is, to temporal changes in the parameter values as governed by mathematical formulas and constraints.

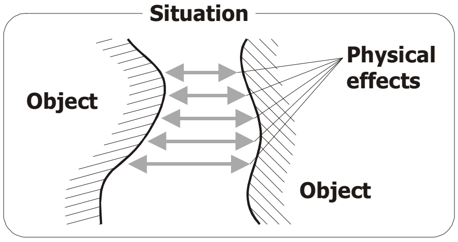

Figure 1: Ontological Conceptualisation of a Nucleus

The objects incorporated in a nucleus are metric entities, which are characterized for their shape and volume. The shape of the objects is represented by half spaces (HS). Actually, a region of these infinite half spaces is used in model building. The finite regions correspond to the natural surface patches of a mechanical part of a product, and lend themselves to effect carrying surface patches. Some of the effect carrying patches will be in contact with surface patches of other mechanical parts. The surface patches are positioned in the model by reference points and may have multiple other reference points for the physical relations assigned to them. For the reason that the geometry of these surface patches is always defined by the geometry of the describing half spaces, in the further discussion we replace the abstract objects in a nucleus with half spaces. Thus, $N = (HS_n, HS_c, \phi, S)$, where HS_n is called a native half space, HS_c is called a complement half space, and ϕ and S are as above. A half space indicates the material domain of an object. Native half space is the term used to identify those half spaces that jointly define the boundary of a mechanical part. Complement half spaces are half spaces defining the boundary of other mechanical parts that are in logical, geometric, positional or physical relation with some native half spaces of a particular mechanical part. Our interpretation allows an object to exist in the nucleus without half space definition. In this case the object is logically identified, but geometrically not specified. This is a substantial assumption that enables incomplete modelling in conceptual design. If the half spaces included in a nucleus are geometrically specified, explicit and implicit analytic surface patches, finite parametric surface patches, or finite discrete point or particle clouds can be used as representations. From the aspects of physical modelling, an arbitrary number of relations can be specified between the pairs of half spaces. For a nucleus to operate, at least one half space must be geometrically specified, but, in this case, only reflexive physical relations can be assigned. Represented by half spaces, the objects acting as ‘environment’ must have at least one reflexive relation to result is a non-limitless system.

The physical relations imply processes that boil down to the behaviour of a nucleus, or a design concept. Actually, the time-dependent changes described by the physical relations will lend themselves to some observable operation, or behaviour, of a nucleus, B, in some situations: $B(N) = \Gamma\ \{S_k\ (o_i\ \phi_{ij}\ o_j)\}$, where o_i , $o_j \in O$, ϕ_{ij} and S_k are as above, and Γ is a behaviour generator function, which takes into consideration the interaction of various nuclei and the influences on each other’s behaviour. The introduction of Γ is necessary, since the observable operation of a modelled design concept, DC, is an aggregation of the elementary operations of the nuclei. For the reason that all nuclei might interact in a composition, this aggregation can be represented as a Descartian product rather than as a Boolean union of the observable elementary operations, that is, $B(DC) = B(N_i) \times B(N_j)$, or $B(DC) = \Pi\ (B(N_i), B(N_j)\ )$, where Π denotes a mathematical product. The arrangement of situations, or in other words, the operation and interaction of the nuclei, are governed by so called scenarios. A scenario, Σ, prescribes a sequence of situations, in which the observable operation delivered by a nucleus or a configuration of nuclei incorporated in a design concept happens. That is, $\Sigma = \cup\ (S_k)$. With these, the behaviour of a DC is: $B(DC) = \Gamma\ (\Sigma\ \{\ N_i\ \})$, or, on the level of relations, $B(DC) = \Gamma\ (\ \cup\ (S_k\ (o_i\ \phi_{ij}\ o_j)))$. Specification of the physical relations includes definition of the parameters, the mathematical formulas (equations and rules) that relate the parameters to each other, and the constraints and value domains. Thus, a nucleus is a primitive system in itself, since its data structure contains all pieces of information that is needed to simulate its behaviour. Based on the above terminology, we call our approach a nucleus-based conceptual modelling of engineering products. At this point we might revisit our previous observation, namely, that engineering products can be modelled in terms of physically coupled pairs (PCP) (Roth 1982). We may say that a PCP is a concrete manifestation of a nucleus, which is able to operate in situations. Examples for such PCP in different situations due to the different arrangement of the objects and the manifestation of physical effects are shown in Figure 2.

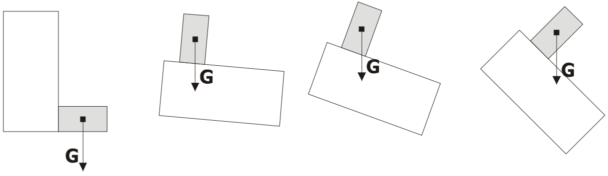

Figure 2: Examples of Situations for PCPs,
From Left to Right: Falling; Not Sliding (Static Friction); Sliding; Turning Over

In simple words, relations express the ways in which objects can stand with regard to one another or themselves. Let O be a set of objects and ϕ a set of relations. The domain of ϕ is the set of objects $o_1 \ldots o_n \in O$ for which there is at least one o_i such that $\phi_i \in \phi$ holds. The converse domain of ϕ is the set of entities $o_1 \ldots o_n \in O$ for which there is at least one o_j such that $\phi_i \in \phi$ holds. The logical sum of the domain and the converse domain is the field of relations ϕ. A universal relation contains both o_i and o_j as arguments. A universal relation is symmetric if $o_1\ \phi\ o_2$ and $o_2\ \phi\ o_1$ hold. A set of reflexive relations contains o_i as argument such that $o_i\ \phi\ o_i$. The square of a set of relations ϕ is $\phi\,|\,\phi$. A set of relations is transitive if each relation contains its square, that is, if $o_i\ \phi\ o_j$ and $o_j\ \phi\ o_k$ hold, then $o_i\ \phi\ o_k$. A relation can be seen as a special sort of objects that connects other objects but is numerically distinct and ontologically independent from the connected objects. If o_i stands in relation ϕ to o_j, but neither its identity nor its nature depends upon o_j, the relation is external. If the opposite is true, then ϕ is internal.

There are two dimensions of thinking about relations. The first one is the context of the relations; the second is the kind of relations. Various types of relations can be considered in various contexts. As contexts of specification of relations we identified mechanical part, assembly and system design (Figure 3). A mechanical part level relation exists in between pairs of native half spaces; therefore, it is called internal relation. If it brings two close neighbour (intersecting) half spaces in spatial relationship, then it is called direct internal relation (DIR). If it concerns two far neighbour half spaces, then it is an indirect internal relation (IDIR). A mechanical assembly relation exists between one-one native half spaces of two mechanical parts, which represent a native-complement construct. The assembly relations are called external relations, and based on the analogy of internal relations, they can also be direct (in contact, DER) or indirect (not in direct contact, IDER). Finally, system-level relations describe interactions with elements of the nuclei representing the physical environments. System level relations offer themselves to the representation of, for example, product-user-environment configurations, as it will be shown from section 8.

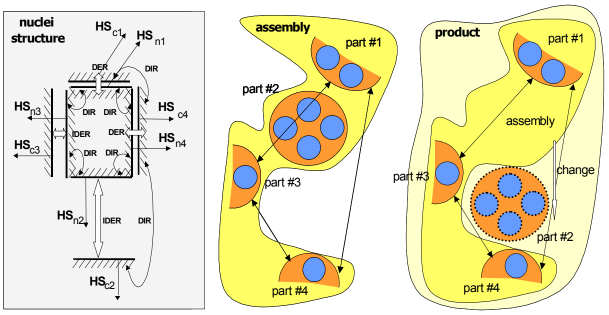

Figure 3: Relations on Mechanical Part, Assembly and System Levels

The type of relations depends on the semantics of the relations. We introduced (a) ontological, (b) connectivity, (c) morphological, (d) positional, and (e) physical relations (Horváth el al. 1998). An ontological relation indicates the existence of an object or any higher-level construct; therefore, it is reflexive. Connectivity relations define the topography of relations between objects and, as discussed above, they are used to define either mechanical parts or assemblies. Reflexive morphological relations define the geometry of the half space describing the metric of an object. Associating morphological relations define the relationship between two half spaces of different objects. Positional relations specify the rotations and translations between the half spaces of a nucleus or any two higher-level constructs. Finally, physical relations formulate physics-based relationships between half spaces of a nucleus to transfer physical effects. They can be reflexive (such as mass) or non-reflexive (such as a force). The relations are described by means of parameters and mathematical formula. The geometric aspect and the effect aspect are brought into synergy through reference points or spots. Based on the nucleus concept, a conceptual modelling system is able to know about and manage a complementing object when a native object is defined. The system is also able to automatically apply all of the default relations for any pair of objects and to let the designer activate only the necessary ones. Based on activating an internal relationship, the system can be aware of the fact that a mechanical part is being formed, and activating an external relationship means that an assembly is generated.

The system can not only monitor these steps of conceptualisation, but also can control the processes and check for validity, completeness and consistence. In system programming, the nucleus concept lends itself to the internal modelling scheme of a CACD system. In fact, it is observable only in the prevailing modelling methodology that focuses on the relations and handling the changes in the relations of objects in various situations. Activation of a nucleus offers a generic modelling entity for the designer that can be further specified according to the design concepts to be applied to solve the design problem. Should a nucleus be activated, the designer is given a set of relations that are specified in terms of attributes, parameters and descriptors. In principle, an infinite number of relations can be specified between two objects, but in practice only those will be instantiated that are important for a given modelling or simulation task (Kitamura et al. 2002).

Parameters representing flow quantities and cross quantities are referred to specific points on the half spaces, which are called ports. In the case of an incomplete part or assembly model, indication of the integrity is a remarkable problem. As a simple solution, fictitious connection lines are generated and visualized between the reference points of the half spaces being in internal positional relations. This leads us to a physically based skeleton model, which is one of the alternative realizations of the nucleus concept as a practical modelling methodology. Naturally, designers do not face these abstract concepts and terms when they are using a nucleus-based system in conceptual design. The design concepts are expressed in terms of an arrangement of nuclei, e.g., in application features, which are represented as functionally related surface patches in given situations. A nucleus can be placed into different situations, which means instantiation of the interacting processes in different forms. Not only complex design concepts, but also design features can be defined in the same manner and used to express design concepts in a semantics-intensive way. Solid mechanics offers the means to treat the four main observable phenomena: motion, collision, deformation and fracture. Phenomena relating thermodynamics, fluid dynamics, gas dynamics, and so forth can also be considered in relations. It is a fact however that there exists no single predictive model that is capable to incorporate all phenomena and interrelated changes, not even theoretically.

8 MODELLING AND SIMULATING PRODUCT USE

In the workflow for modelling and simulating product use, three basic activities are involved: (1) modelling the actor triplet *U, P* and *E,* (2) modelling a scenario and (3) performing a simulation.

To model the actor triplet, instantiations of nuclei serve as building blocks for the actors *U, P* and *E.* The fact that nuclei can represent the physical characteristics of the actors in addition to their geometric and structural characteristics makes them attractive for modelling and simulation of use cases.

A scenario is an arrangement of situations that can be used as input for simulations, $\Sigma = \cup (S_k)$. A situation is a state of the actors that allows the description of different circumstances. By describing a particular configuration of the actors *U, P* and *E*, each situation defines the physical processes to be simulated as well as the initial state of the system, from which simulation algorithms can calculate the course of physical processes. In simulation, the scenarios are the formalized means to treat the circumstances. They can be seen as a kind of program: the simulation engine works according to the control that comes from the scenario. The scenario connects to the mental part of the designer as a means to formalize happenings the designer expects in terms of the three actors. In this context, the scenario serves as a formalization of the design intent: it is a connection between the designer and the triplet that allows the designer to play with the simulated triplet. At the same time, scenarios allow the designer to include the effects of mental processes of the user that cannot be covered by the deterministic algorithms of common simulation engines. In that context, the scenario can be seen as a use pattern for a product.

To overcome the problem that simulations cannot cope with multiple use processes, produced by a multitude of users, user behaviours, and environments, scenarios can also be applied to generate and manage multiple simulations.

9 INFORMATION CONTENT OF THE PRODUCT-USE MODEL

The conceptual model consists of (1) an object-type model based on the nucleus principle and (2) scenarios. The nucleus model also incorporates a relevant set of relations that make it possible to define the associations between *U, P* and *E* and simulate the use through a series of situations. To make the abstract concepts more tangible, we arrange the discussion around a practical example.

9.1 The actor triplet

Figure 4 shows a schematic representation of a simple *U-P-E* model. The illustrative 'product', *P,* is a foot-operated lever that can be used to lift objects. The objects that are not part of the product are considered to be part of the environment *E*. As the figure shows, the interactions between the actors and between parts of actors take place on the specified regions of the contact surfaces, which are represented by finite surface patches.

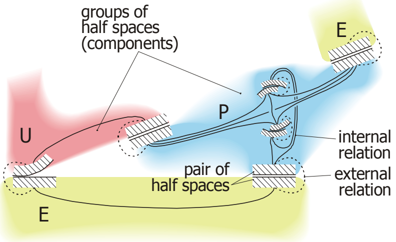

Figure 4: Nucleus-based *U-P-E* Model with Internal and External Relations

Point-oriented relations are assigned to the reference points of these surface patches. The surface patches on the half-spaces belonging to the same part of the same actor are connected through internal relationships. Figure 5 shows the topography of the relation structure between patches in an abstract form. With the edges associated as they are representing internal relationships (forming a component) or external relationships (forming an assembly), it serves as a conceptual scheme to organize the computer-internal database.

9.2 Scenarios

It is important to note that, while Figure 5 represents a generic situation, Figure 4 concerns a particular situation. A particular situation assumes a given configuration of the contact surface patches and a given manifestation of the physical effects in the presented situation: the foot presses the lever, friction and gravity impede the rotation of the lever and the lever takes a definite spatial position. Other situations could be when the foot releases the lever upward, or situations in which the object or the foot is absent, or in which they are swapped. A *scenario* contains at least one situation, for there is at least one initial state from which the physical processes can be launched. Other states that cannot straightforwardly be derived from these processes, i.e., not from the associated simulation, must be defined in other situations within the scenario. A typical use scenario for this lever would consist of a series of situations that can be qualitatively described as: (1) no foot present, the right end of the lever is down and there is an object placed on it, (2) the foot pushes the lever to lift the object, (3) the object is removed at a certain height and the foot releases the lever to make the right of the lever end come down. Note that the situations that are introduced in (2) and (3) depend on decisions from the human user, and that they cannot be calculated by a deterministic simulation algorithm starting from (1).

Elaborating the information content of scenarios, we will take a closer look at situations first. Practically, situations define how and where *U, P* and *E* interface/interact with each other, and which initial configuration the individual parts of *U, P* and *E* are supposed to be in. In case of the user, this configuration refers to the posture that is governed by degrees of freedom of the joints and the skeleton. P and E can also be assumed to be in various configurations based on degrees of freedom, which always implies different situations. These configurations, or degrees of freedom, typically appear as *simulation parameters,* i.e., parameters that are variable within a simulation. They have to be distinguished from *design parameters,* i.e., parameters that can be chosen by the designer. For instance, the mass of a component is typically a design parameter because the designer can change it, but it normally does not change during a physical process in use. Conversely, an arbitrary intermediate angle that the lever in Figure 5 can assume is a typical simulation parameter: it does not make sense to define it as a design specification. On the other hand, the maximum and minimum angles for the lever can be considered both design parameters and simulation parameters.

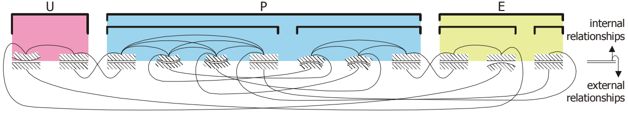

Figure 5: Internal Representation of the Nucleus-based *U-P-E* Model

Through the situations, the scenario imposes simulation parameters over the modeled environment. We can distinguish input, throughput and output simulation parameters. The throughput and output parameters receive values by inheritance from the input parameters with the contribution of the design parameters. The output reflects the change caused by whatever happens in the system.
The connection between the various situations that a scenario feeds to the simulation is made through conditions described in terms of variables. If a certain condition occurs during the simulation, the scenario prescribes that a new situation comes into effect and the simulation has to continue from there. The condition can be a value of a simulation parameter, or the time elapsed from the latest specified situation.

10 APPLICATION EXAMPLE

To investigate the applicability of resource-integrated modelling and simulation in conceptual design, we have developed a nucleus-based model of an existing product, a pedal bin. The level of detailing of the object-type models of *U*, *P* and *E* corresponds to what we presumed to be appropriate in conceptual design. We generated a qualitative description of a simple use scenario, disposal of a piece of garbage, which specifies the situations and the initial conditions for a simulation. The actual simulation was performed with Working Model® 2D (WM2D), a product of MSC Software Corporation (Wang 2001). This package was also used to create most of the nucleus-based models of *U*, *P* and *E*.

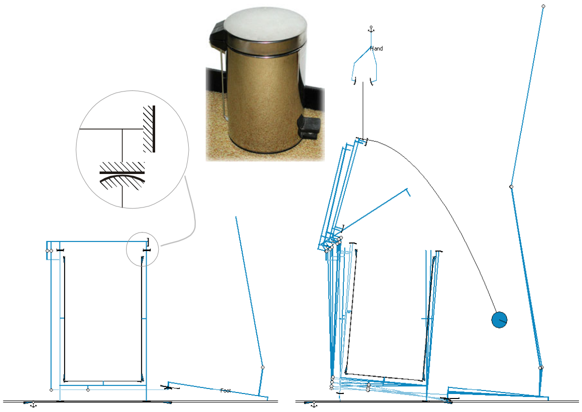

Figure 6. (a) The Nucleus-Based Conceptual Model of the Pedal-Bin (Left);
(b) the Result of Applying a Use Scenario (Right)

The reason why we chose WM2D is its distinctive capability to support situations that do not only depend on one initial state, but may include predefined interventions afterwards. In case of the pedal-bin, the user's hand can drop the object at any given time, or the time of dropping can depend on the position of the lid. Likewise, the moment when the pedal is released can depend on the position of the dropped object. Many commercial simulation packages cannot directly include such interventions. Figure 6a shows the initial resource-integrated conceptual model of the pedal bin for investigation of use. Only those parts of the user's body have been modelled that are concerned in the use scenario: a hand and a foot (note: in this pilot study, it was not our primary objective to come up with a correct anatomic representation of the human body, or to provide exhaustive forecasts for real-life design process). The model of the product consists of four moving parts, and the environment consists of the floor and the garbage object. The grey rods represent skeleton elements, and the half-spaces are indicated by the black outlines. Note that for graphical reasons, we used the common representation of a dot in a circle to represent joints rather than the half-space representation depicted in Figure 5. Half-spaces are graphically represented at those locations where components interact at $t=0$, or where interaction can be conceived during the situations defined in the scenario. The simulation is based on a scenario arranging two situations starting from the following two states: (1) the foot exerts a constant force F_1 on the pedal (i.e., to operate the lid) and (2) if the condition $t=1s$ is met, the reaction force that keeps the garbage object in the hand is set to $F_2=0$ (i.e., the object is released), while F_1 remains unchanged.

Figure 6b shows the results of the simulation: when the pedal is pressed, the bin starts to tumble and the lid tends to oscillate around its highest position. If the object is launched from the shown position, this behaviour of the bin prevents proper disposal.

Figure 7 shows an improved conceptual design with a counterweight connected to one side of the lid. It ensures a more determined movement of the bin and the lid. The simulation proved that the object launched at the same time and from the same location as in Figure 6, now lands successfully inside the bin. As an all-embracing definition of the use scenario, a third situation was added and investigated in the simulation: (3) from t=1.5s, $F_1=0$, i.e., the foot releases the pedal to close the lid.

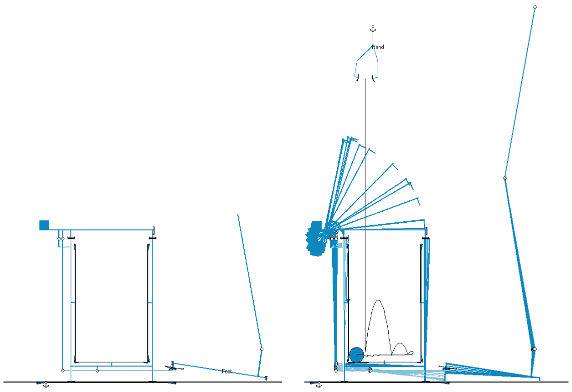

Figure 7: Simulation Result of a Use Scenario with Improved Conceptual Design of the Pedal Bin

11 DISCUSSION

Despite the experienced restrictions, the results revealed attractive prospects for the application of resource-integrated models to represent use-processes in conceptual design. Designers can anticipate the use process without having to switch between object-type models and process-type models (including functional models). That is, processes involving simulation-based forecasting can be seamlessly included in the modelling environment, and even intervention-type interactions can be studied.

The proposed nucleus concept offers relation-oriented modelling rather than entity-centred modelling. It places the pairs of objects into a multitude of relations, which are not restricted to be in the same aspect or context. By doing so, it mimics the working of the human mind as it builds associations between neutral entities in a creative conceptualisation. It also tries to resolve the known problem of linking different views or jumping between aspects.

By making the entity relationships more explicit and knowledge intensive, a nucleus-based conceptual design system converts the paradigm of 'doing what you know' to the paradigm of 'knowing what you're doing'. It allows the designers to describe design concepts as an aggregation of nuclei, to define and use application features, to construct parts, assemblies and systems, and to investigate the physical behaviour of all these constructs based on space- and time-dependent evaluation of the specified relations. It involves validity management, consistency management and multi-view management. An obvious advantage of the nucleus concept is that it does not force the designer to define the part geometries first. He may alternate between structure, component and system definition, leaving the geometry to appear as a by-product of the conceptualisation process.

The nucleus concept vindicates that models can be incomplete on part, assembly and system levels. Models can gradually be extended and refined as knowledge becomes available for the designed product. Extension and refinement may take place in terms of the morphological and physical relations. This way, the evolving model that integrates both artefact/actor representation and process representation adapts to the progress of conceptualisation. This model is referred to as a multi-resolution model.

Current research deals with extensional relations only, and considers them as n-ary relations that can be traced back to dyadic relations. The used prepositional functions do not extend to intentional relations.

Note that we still face some sort of 'metaphysical' limitations in terms of being able to define any ideal modelling entity for the reason that an exact scientific understanding related to the following issues is still missing: (a) mapping requirements onto a system of functions or potential operations, (b) mapping target functions to first principles and physical processes, (c) mapping functions or structures to forms and embodiments, (d) deriving structures from first principles and physical phenomena, and (e) identification of the necessary constituents from physical processes.

Our application case study, on the one hand, demonstrated the method and issues of using nucleus-based modelling in conceptual design. On the other hand it made it possible for us to see the advantages and disadvantages with respect to the given application case.

The homogenous representation of *U, P* and *E* utilized in the use-oriented modelling and simulation of the concept product, i.e., the pedal bin, enabled us (1) to model the known use processes in the form of common scenarios and (2) to predict ad-hoc use processes based on simulations.

As a result of the investigations and, in particular, of forecasting the behaviour, an improved concept product could be realized on the level of detail that is typical for conceptual design. Thus, our hypothesis seems to be proven at least for the presented application example. It is likely that the same can be claimed for products of a similar (low) complexity and of resembling use processes. Nevertheless, we have to validate it for a wider range of products and use processes. In this respect it has to be made clear that in terms of an exhaustive validation of the hypothesis, the set-up of this tabletop research was inherently limited by the capabilities of the simulation package. WM2D does not support object-type models and processes of high complexity, since (1) it cannot deal with three-dimensional representations, (2) it has difficulties in dealing with statically undetermined structures, and (3) it has been developed for rigid-body dynamics. Moreover, it has difficulties in dealing with conceptual modelling entities that do not necessarily correspond to actual geometries with corresponding weight distributions, such as the skeleton elements and of surface patches of half-spaces that we applied. This indicates that there is a need to develop a dedicated simulation environment for resource-integrated models.

12 CONCLUSIONS AND FUTURE WORK

For a typical, however simple, application, we have shown that a nucleus-based model that offers a homogenous representation for the product, the user and the environment can support conceptual design of products. This comprehensive, resource-integrated model allows a designer to consider known use processes in various situations, but also to obtain predictions of ad-hoc use processes by means of simulation. The results of these behavioural simulations can be utilized in conceptual design to improve products for use. To make the resource-integrated models and the forecasting of use processes applicable to a wider range of products and use processes, further work is needed in particular in (1) further refinement of the fundamentals and methodology of modelling and simulation based on scenarios prescribing the use of products, and (2) development of a dedicated simulation environment that can benefit from resource-integrated conceptual models. It is expected that a full-featured system can be developed based on these future achievements to assist designers in optimizing products for use in the early stages of development.

13 REFERENCES

Badler N.I, C.B. Phillips, B.W. Webber. 1993. *Simulating humans – computer graphic animations and control.* Oxford University Press, New York.

Bailey, C., G.A. Taylor, M. Cross, P. Chow. 1999. "Discretisation procedures for multi-physics phenomena." *Journal of Computational and Applied Mathematics* 103, 3-17.

Baraff, D., Witkin, A. 1998. "Large steps in cloth simulation." *Proceedings of SIGGRAPH*, 43-54.

Bryant, C.R., M.A. Kurfman, R.B. Stone, D.A. McAdams. 2001. "Creating equation handbooks to model design performance parameters." *Proceedings of ICED*, Glasgow, 501-508.

Finger, S., X. Chan, R. Lan, B. Cahn. 2001. "Creating virtual prototypes - integrating design and simulation." *Proceedings of ICED*, Glasgow, 485-492.

Forbus, K.D. 1984. "Qualitative Process Theory." Artificial Intelligence, Vol. 24, 85-168.

Horváth, I., G. Kuczogi, J.S.M. Vergeest. 1998. "Development and application of design concept ontologies for contextual conceptualization." *Proceedings of ASME DETC*, Atlanta.

Jansson, J., J.S.M. Vergeest. 2000. "A General Mechanics Model for Systems of Deformable Solids." *Proceedings of TMCE.*, Delft.

Kitamura, Y., T. Sano, K. Namba, R. Mizoguchi. 2002. "A functional concept ontology and its application to automatic identification of functional structures." *Advanced Engineering Informatics*, Vol. 16, No. 2, 145-163.

Koch, R.M., M.H. Gross, A.A. Bosshard. 1998. "Emotion editing using finite elements." *Eurographics*, Vol. 17, No. 3, 295-302.

Mah, S., T.W. Calvert, W. Havens. 1994. "A constraint-based reasoning framework for behavioural animation." *Computer Graphics Forum*, 13 (3), 315-324.

Mahoney, D.P. 2000. "Multiphysics analysis." *Computer Graphics World*, 23 (6), 44-46, 50, 52.

Martens, D. 1998. "Neural networks as a tool for the assessment of human pilot behaviour in wind shear." *Aerospace science and technology*, Vol. 1. 39-48.

Masini, R., Padovani, E., Ricotti, M.E., Zio, E. 1998. "Dynamic simulation of a steam generator by neural networks." *Nuclear Engineering and Design*, Vol. 187. 197-213.

Noort, A. 2002. *Multiple-view feature modeling with model adjustment.* Ph.D. Thesis, Delft University of Technology, Delft.

Park J. and D.S. Fussell. 1997. “Forward dynamics based realistic animation of rigid bodies.” *Computers and Graphics*, Vol. 16, 483-496.

Pop, C., A. Khajepour, J.P. Huisson, A.E. Patla. 1999. “Application of Bondgraphs to Human Locomotion Modeling.” *Proceedings of HKK Conference*, Waterloo, Canada, June, 85-90.

Porcher Nedel, L., D. Thalmann. 2000. “Anatomic modeling of deformable human bodies.” *The Visual Computer*. Vol. 16, 306-321.

Redfield, R.C., S. Krishnan. 1992. “Towards automated conceptual design of physical dynamic systems.” *Journal of engineering design*, Vol. 3, No. 3. 187-204.

Riley, K.F., M.P. Hobson, S.J. Bence. 1997. *Mathematical methods for physics and engineering*. Cambridge Press, Cambridge.

Roth, K.-H. 1982. *Konstruieren mit Konstruktionskatalogen*. Springer Verlag, Berlin.

Terzopoulos, D., J. Platt, A. Barr, K. Fleischer. 1987. “Elastically deformable models.” *Computer Graphics*, Vol. 21, No. 4, 205-214.

Therrien, R.G., P.A. Bourassa. 1982. “Mechanics application to sports equipment: protective helmets, hockey sticks, and jogging shoes.” In: *Human body dynamics: impact, occupational and athletic aspects,* Ghista, D.N. (Ed.). Clarendon Press, Oxford.

Van der Vegte W.F. and I. Horváth. 2002. “Consideration and modeling of use processes in computer-aided conceptual design: a state of the art review.” *Transactions of the SDPS*, Vol. 6, No. 2, 25-59.

Van der Vegte W.F., Y. Kitamura, R. Mizoguchi, I. Horváth. 2002. “Ontology-based modeling of product functionality and use – part 2: considering use and unintended behavior.” *Proceedings of EDIProD*, Łagów, 115-124.

Wang, S-L. 2001. “Motion simulation with working model 2D and MSC.visualNastran 4D.” *Journal of Computing and Information Science in Engineering*. Vol. 1, No. 2., 193-196.

Zeid, A.A., Overholt, J.L. 1995. “Singularly perturbed formulation: explicit modeling of multibody systems”, *Journal of the Franklin Institute*, Vol. 332B No. 1, 21-45.

Zienkiewicz, O.C, R.L. Taylor. 2000. *The finite element method*. Vol. 1,2,3. Butterworth-Heinemann, Oxford.

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