INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

NUCLEUS-BASED PRODUCT CONCEPTUALIZATION - PART2: APPLICATION IN DESIGNING FOR USE

W.F. van der Vegte, I. Horváth

Abstract

A significant potential for improvement of products lies in anticipation of various use cases when products are being designed, especially in conceptual design where there is a multitude of options for the designer. This paper presents a methodology to generate resource-integrated models unifying representations of the product, the user and the environment based on nucleus modelling, which is presented in Part I of this paper, according to scenarios that describe the use of products. This homogenous representation allows modelling both from an object point of view and a process point of view. A designer can model known use processes and obtain simulation-based predictions of ad-hoc situations. The nucleus is the lowest level modelling entity that can be used equally well in representing the three actors. The time-dependent relations allow behavioural simulation in space and time that is the basis of use-process modelling and forecasting. A case study is presented that clarifies the method of application and the achieved results. The simulation was based on a single scenario; management of multiple scenarios is an issue that remains for future research.

Keywords: Designing for use, conceptual design, computer-aided design, simulation, process modelling

1 Introduction

It is widely recognized that knowledge-intensive models can improve the efficiency of design processes and thus contribute to the anticipation of what happens with products during their life cycle. In this context, this paper focuses on anticipation of use processes during conceptual design. In this early stage of design, designers typically create the first concrete models of products. Unfortunately, the modelling techniques and representations currently used in analysis and behavioural simulation do not provide effective means to model the use of products. One of the reasons is that in modelling use, not only the product *(P)* has to be modelled, but also the user *(U)* and the environment *(E)*. The concrete problems with the available geometry-oriented modelling environments and simulation tools are: (1) the created models are supposed to be complete and valid, which is not necessary in conceptual design; (2) the simulations are orientated towards the behaviour of artefacts in a given environment, but they typically only include passive[1] behaviour of the human; (3) unlike knowledge describing the pure physical behaviour of *P* and *E*, knowledge related to the active behaviour of *U* cannot straightforwardly be embedded in geometry; (4) knowledge that associates *P* with different

[1] 'Passive' refers to behaviour where a body is deformed or moved by external impact only. Conversely, 'active' behaviour refers to behaviour where a body is deformed or moved by internal muscular activity.

*U*s and different *E*s cannot be included; (5) simulations tend to be restricted to behaviour that is completely determined by one initial state. Consequentially, current simulation packages cannot cope with interventions that naturally occur in use processes.

We do not intend to introduce a separate knowledge model in addition to the common product model. What we need instead is a so-called *resource-integrated model* that incorporates use-process knowledge in conceptual models and extends the product model with knowledge about the user and the environment, as well as with scenarios prescribing typical use situations. The aim of our research has been to employ such models together with smart simulation algorithms to model and forecast use during conceptual design.

Our research covered a study of the related literature and systems, elaboration of a new concept and framework for use-process modelling as well as the development of a pilot implementation to test the ideas. In this paper, we present the methodology that enables us to generate resource-integrated models to describe the use of products. It provides a template to specify the content of the models and a procedure to apply it 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 known use processes in various situations, but also the prediction of 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, that is, by applying the method to a sample case.

We focused on bringing *U*, *P* and *E* together into an extended conceptual product model that can be deployed as a basis for use-process simulation in conceptual design. In association with such models, we also inaugurated the notion of use scenarios but yet we did not elaborate on deriving use-process models based on predefined scenarios. As far as knowledge processing is concerned, we adapted the solution that was presented in one of our earlier publications [1]. The use-oriented conceptual model, including information on *U*, *P* and *E*, has been realized in a commercially available system as a test-bed. We had to overcome considerable limitations and had to accept compromises in terms of the completeness of implementation, but the commercialised simulation software relieved us from the efforts that would have been needed to develop a new simulation engine from scratch.

2 Consideration of use in computer-aided conceptual design

Earlier, the authors presented a survey on the consideration of the use of products in computer-aided conceptual design [2]. 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 a concise discussion of the core problem of modelling use processes in the course of product conceptualisation and early simulation. The use of products can be defined as ‘employment or application to a purpose’ [3] 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’ [4]. Use is an interaction between the three actors, *U, P* and *E*, involving mutual exchange of matter, energy and information. In considering use in modelling, we can distinguish three approaches that can be followed, which may appear combined in practice: (1) design for usability, (2) use-process modelling, (3) object-type modelling of *U, P* and *E*, and (4) numerical simulation of behaviour.

(1) ‘Usability’ is a concept that became popular in assessing the use-related qualities of prod-

ucts. However, usability knowledge has only been applied in design for common stereotypical products, where experience has produced concrete criteria to determine the usability. Examples of such criteria are dimensions for furniture, or the preferred force to operate a switch.

(2) A variety of process models has been more successfully applied to include use aspects in conceptual design (e.g., [5], [6], [7]). These models, however, focus on discrete process representations and cannot capture knowledge about, and predict the behaviour of, *U, P* and *E*. To some extent, however, they are capable to represent certain types of scenarios.

(3) Numerous modelling techniques can be used to represent products, environments *and* users as objects in space. These widely accepted techniques do generally not incorporate the pieces of information needed to forecast or represent processes. Considering the fact that designers prefer working with object-type representations rather than process representations as a starting point, including use-process knowledge in object-type models seems to be a reasonable approach. However, we have to overcome the problem that the majority of spatial modelling techniques require a complete and valid definition of the geometry and the structure, which makes the direct application in conceptual design somewhat difficult. The nucleus-based modelling, of which the fundamentals have been presented in Part I of this paper, lends itself to an attractive solution of this problem.

(4) Numerical simulation techniques can successfully be employed to predict the behaviour of object-type models. Practically, the only notable exception is the active behaviour of the user, mainly because its non-deterministic nature. Promising techniques are emerging for simulating humans in areas laterally related to design, such as computer-graphics animation [8], [9], and artificial intelligence based behavioural simulation techniques [10], [11], [12]. These simulation techniques open up the way to a more realistic prediction of use although they represent active human behaviour through deterministic algorithms. In reality, the active behaviour of humans is controlled by mental processes, which make it non-deterministic. What has already been achieved is realistic-*looking* simulations in certain computer-graphics applications, such as computer games or Sci-Fi movies, which do however not have the potential to be applied as predictive simulations in conceptual design. Another weakness of simulation techniques is that they cannot handle multiple scenarios that have to be dealt with for three reasons: (1) the possible multiple outcomes of non-deterministic human behaviour, (2) multiple users, and (3) multiple environments.

It does not seem to be very likely that one will ever be able to consider all possible users and environments, and all possible interventions commenced by the, sometimes irrational, active behaviour of users. However, for many products, a considerable amount of such knowledge can be gathered, for instance, from historical data (e.g. from existing and similar products). Thus, what we can do is to collect knowledge available about users, user's behaviour and environments in a knowledge base, and to apply simulation techniques to investigate the more or less deterministic behaviour. The collected knowledge will never cover all possible uses, but will most likely cover many more forms of use than a designer may think of. In [1], which was a result of collaboration with the department of knowledge systems at Osaka University, we presented how *ontologies,* a concept for representing complex knowledge structures from the field of knowledge engineering [13] can be employed to handle this knowledge and make it available in conceptual design.

3 Fundamentals of model generation

The ultimate goal of our research in modelling and forecasting use in conceptual design is to develop a system to generate resource-integrated models. In this paper, we focus only on the generation of kernel *U-P-E* models. The models are partly generated based on knowledge about use stored in ontologies, partly by the designer applying his or her own insights. For forecasting use processes, the knowledge in the models has to provide input for simulations. To overcome the problem that simulations cannot cope with multiple use processes, produced by a multitude of users, user behaviours, and environments, our idea is to apply multiple simulations based on scenarios, which can be associated with the *U-P-E* system in order to provide the starting conditions for simulations and forecasting. In the resource-integrated model, they are the carriers of the process knowledge that complements the physical behaviour processed in simulations and that usually cannot be captured in object-type models. A scenario is an arrangement of situations, forming together a use pattern for a product. 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 this initial state, the course of the processes belonging to the use situation can be calculated from the physical process knowledge in the simulation package. 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 (and not from the associated simulation) must be defined in other situations within the scenario. 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.

As presented in Part I of the paper, instantiations of nuclei serve as building blocks in modelling 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. Furthermore, it is also possible to consider them as function carriers, and to include them in a functional ontology [14]. This ontology can incorporate the scenarios consisting of situations known to occur in use processes. In principle, any existing simulation environment can be used to predict the behaviour of *U*, *P* and *E*, as long as it can represent intervening interactions as is implied by the situations prescribed in the use-process scenarios.

In the generation of models, we distinguish two cases: (a) conceptual design of a new product and (b) conceptual redesign of an existing product or of a product belonging to a known class of products. In generating resource-integrated models, four activities are involved: modelling the user, modelling the product, modelling the environment, and modelling a scenario in which *U, P* and *E* appear as a system, involving situations that can be used as input for simulations. There is no prescribed chronological order for modelling *U, P* and *E*, but of course all of the three models are needed as input for a scenario. Multiple scenarios considered in a design process appear as iterations of activity (4). If scenarios involve different users, different environments and/or modified versions of the product, activity (1) and/or (2) and/or (3) is also iterated before a given scenario can be simulated.

The options for a designer to combine his or her ideas with existing knowledge to create the models depend on the type of product development. In case (b), more knowledge, or even complete models, can be available than in case (a). To model the user, the product, the environment and the scenarios, respectively, the following procedures are available to the designer:

- For the *user*, both in case (a) and (b) an initial model is retrieved from the ontology[2]. Depending on the product and the environment it can be a model representing the entire human body or just certain parts of it. Typically, the user model is not edited by the designer, but it is generated to represent a given individual in a user population.
- For the *product,* in case (a), the generated model is as described in Part I of this paper. In case (b), an initial model is retrieved from the ontology, which can be edited by the designer like in the first case.
- For the *environment,* both in case (a) and (b), the initial models representing common use environments are retrieved from the ontology. In case (b) the initial model can be more specific with regard to the known product class. It is possible in both cases that models have to be edited or completely new models have to be created as with product models.
- The procedure for modelling *scenarios* is not elaborated here. It is assumed that in case (a), this is done by the designer, and that in case (b), an initial model is retrieved from the ontology, which can be edited by the designer.

In the further parts of the paper, we deal with the information content and generation of conceptual models for use assessment. The conceptual model is an object-type model but it also incorporates a relevant set of relations that make it possible for us to define the relationships between *U, P* and *E* and simulate the use through a series of situations. As a fundamental principle of model building, the nucleus concept will be used. In order to make the abstract concepts more tangible and transparent, we arrange the discussion around a practical example.

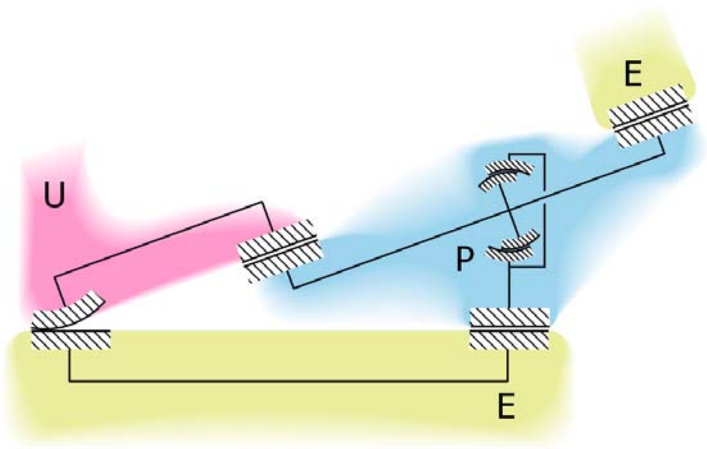

Figure 1. Nucleus-based *U-P-E* model

4 Contents of the product-use model

Figure 1 shows schematic representation of a simple *U-P-E* model. Note that this example can be extended almost arbitrarily in the context of modelling for use. 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

[2] We intend to use a multimedia-type ontology, which is carrying knowledge in multiple representations rather than just in lexico-grammatical formats.

between the actors and between parts of actors take place on the specified region of the contact surfaces, that are represented by finite surface patches. 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 by skeleton elements that represent the internal relationships. The relations between various contact surface patches of different actors are also connected by skeleton elements. This representation is called the topography of the relation structure and it serves as a conceptual scheme to organize the computer-internal database. Figure 2 shows this conceptual scheme, with the edges associated as they are representing internal relationships (forming a component) or external relationships (forming an assembly).

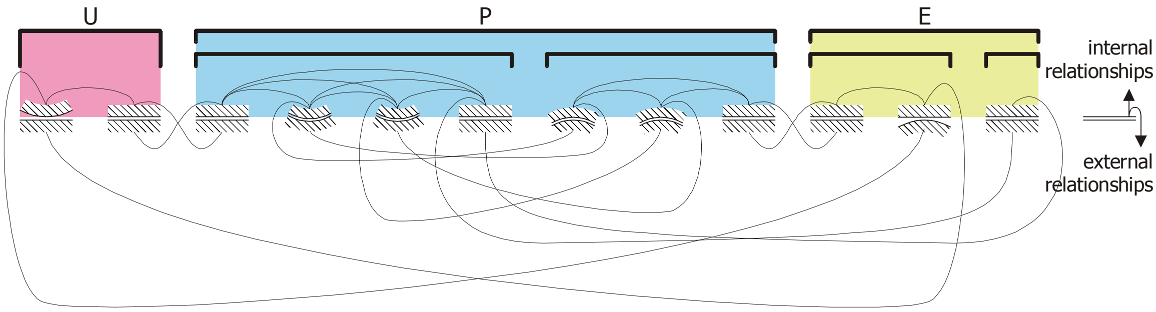

Figure 2. Internal representation of the *U-P-E* model shown in Figure 1.

It is important to note that, while Figure 2 represents a generic situation, Figure 1 concerns a particular situation. It is a particular situation because it 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, for instance, when the foot releases the lever upward, or situations when the object or the foot is absent, or when they are swapped. A typical use scenario for this lever would consist, for example, of the following situations: (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.

5 Application example

To investigate the applicability of resource-integrated modelling in conceptual design, we have developed a nucleus-based model 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. In our understanding it represents what the ontology can provide for us as a basis for a use-oriented redesign of an existing product – case (b). But it can also be understood as an intermediate stage in the conceptual stage of a new product – case (a). 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 [15]. This package was also used to create most of the nucleus-based models of *U*, *P* and *E* [3].

[3] The complex shapes required for the symbolic representation of the regions of the half-space elements were created with a vector-based graphics package and imported into WM2D.

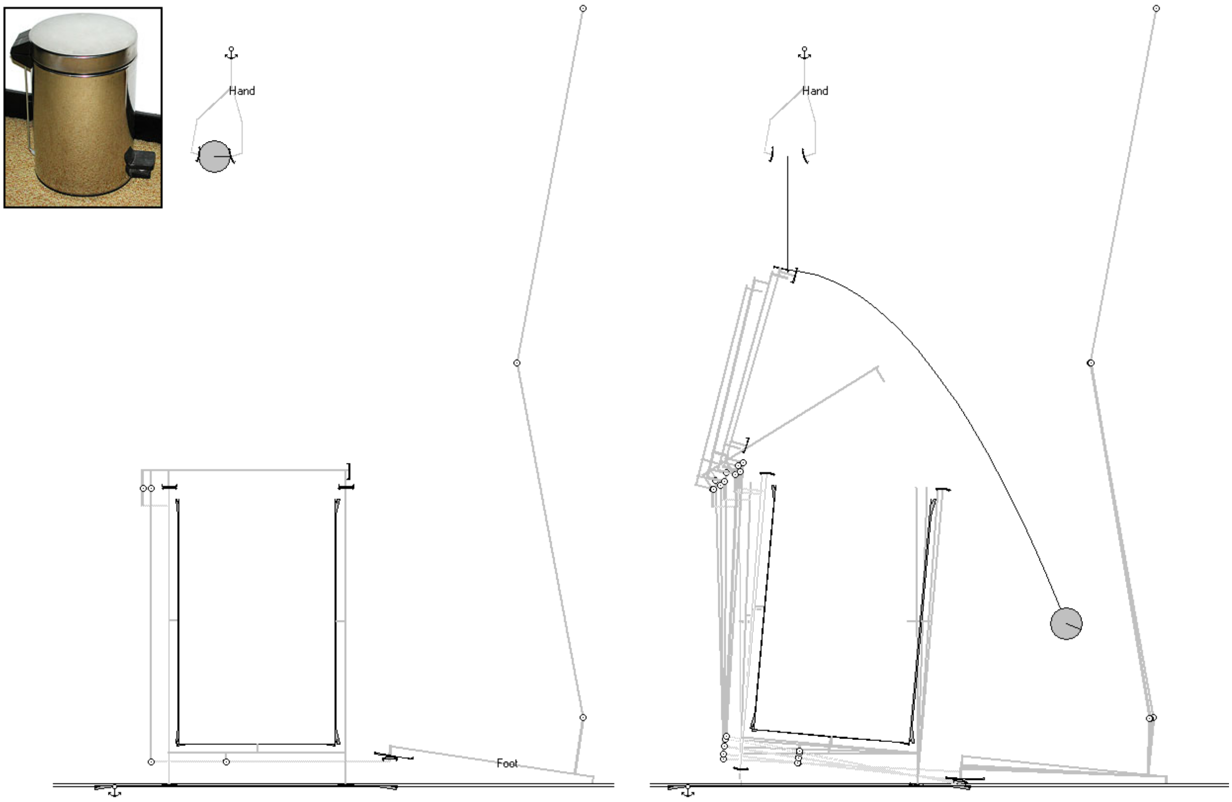

Figure 3. (a) The nucleus-based conceptual model of the pedal-bin (left);
(b) the result of applying a use scenario (right)

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 3a 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[4]. 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 1. 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 pushes down the pedal to operate the lid and (2) at *t=1s,* the hand releases the garbage object to be dropped into the bin.

Figure 3b 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.

[4] In this pilot study, it was not our objective to come up with a correct anatomic representation of the human body, or to provide exhaustive forecasts for real-life design process. Such refinements would depend on the availability of a use ontology, which had not yet been created at this stage of the research.

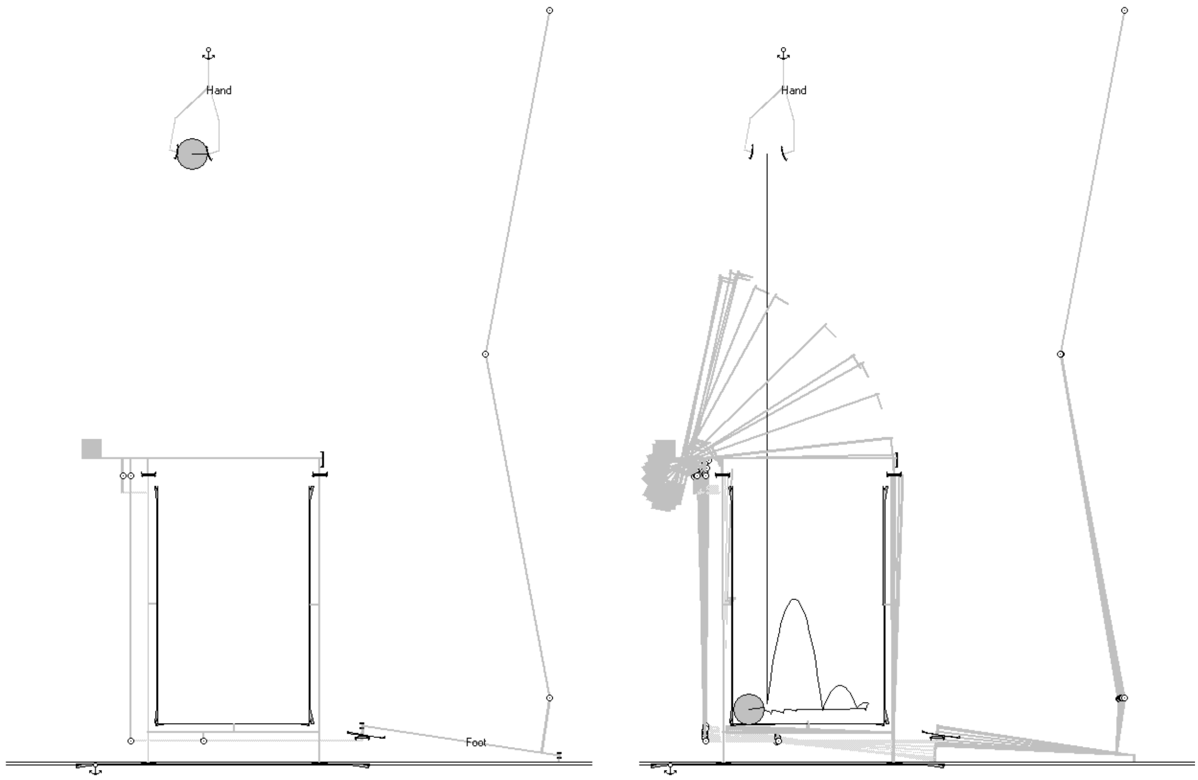

Figure 4. (a) Improved conceptual design of the pedal bin (left);
(b) simulation result of a use scenario (right)

Figure 4 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 3, 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: the foot releases the pedal to close the lid.

6 Discussion

On the one hand, our application case study 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 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 the set-up of this tabletop research has got *a-priori* limitations in terms of an exhaustive validation of the hypothesis, for two reasons: (1)

the generation or retrieval of known use processes was not based on a fully developed use ontology, nor on fully elaborated scenario-based modelling, and (2) the applied simulation technique offered by the WM2D system also posed limitations.

The first issue speaks for itself, while it gives general directions for future research activities. The same can be said for the second issue, but in a more specific sense. WM2Ddoes 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 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.

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 consulting external knowledge sources about, and models of, users and environments, and 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.

7 Conclusions and future work

For a typical application, we have shown that conceptual design of products can be supported by a nucleus-based model that offers a homogenous representation for the product, the user and the environment. 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 the following areas: (1) further development of the methodology and technology for capturing and processing knowledge related to the use of products, (2) further refinement of the fundamentals and methodology of modelling based on scenarios prescribing the use of products, and (3) 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.

References

[1] van der Vegte W.F., Kitamura Y., Mizoguchi R., Horváth I., "Ontology-based modeling of product functionality and use – part 2: considering use and unintended behavior", Proceedings of EDIProD' 2002, Łagów, 2002, pp. 115-124.

[2] van der Vegte W.F. and Horváth I., "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, 2002, pp. 25-59 (also available at http://www.sdpsnet.org/onlinejurnal.html).

[3] Fowler H.W. and Fowler F.F. (eds.), "The concise Oxford dictionary", Clarendon Press, Oxford, 1961.

[4] Dirken J.M., "Productergonomie – ontwerpen voor gebruikers" (in Dutch, *"Product ergonomics – designing for users"*), Delft University Press, Delft, 1997.

[5] Buur J., Windum J., Jakobsen M.M., "Man-machine interface design needs systematic methods", Proceedings of ICED '91, Zurich, 1991, pp. 741-746.

[6] Otto K.N. and Wood K.L., "Customer integrated systematic design", Transactions of the SDPS, Vol. 3, No. 4, 1999, pp. 61-74 (also available at http://www.sdpsnet.org/onlinejurnal.html).

[7] van der Vegte W.F., Pulles J.P.W., Vergeest J.S.M, "Towards computer-supported inclusion and integration of life-cycle processes in product conceptualization based on the process tree", Automation in Construction, Vol. 10, 2001, pp. 731-740.

[8] Cerezo A., Pina A., Serón F.J., "Motion and behaviour modelling: state of the art and new trends", The Visual Computer, Vol. 15, 1999, pp. 124-146.

[9] Park J. and Fussell D.S., "Forward dynamics based realistic animation of rigid bodies", Computers and Graphics, Vol. 16, 1997, pp. 483-496.

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

[11] Bordeux C., Boulic R., Thalmann D., "An effcient and flexible perception pipeline for autonomous agents", Eurographics, Vol. 18, 1999, No. 3, pages not numbered.

[12] Jung M-R., Badler N., Noma T., "Animated human agents with motion planning capability for 3D-space postural goals", Journal of Visualization and Computer Animation, Vol. 8, 1994, pp. 225-246.

[13] Kitamura Y., Mizoguchi R., "Ontology-based description of functional design knowledge and its use in a functional way server", Expert Systems with Application, Vol 24, No. 2, 2003, pp. 153-166.

[14] Kitamura Y., Mizoguchi R., "Organizing knowledge about functional decomposition", Proceedings of ICED '03, Stockholm, 2003.

[15] Rivera T., Mitiguy T. (last revisers) "Working Model – User's Manual", MSC Software Corporation, San Mateo, 2001.

For more information please contact:

Wilfred van der Vegte MTD
Section of Computer Aided Design and Engineering
Faculty of Industrial Design Engineering, Delft University of Technology
Landbergstraat 15, 2628 CE Delft, The Netherlands
Phone: 00+31 15 278 1061, Fax: 00+31 15 278 1839
E-mail: w.f.vandervegte@io.tudelft.nl